

SILICON MATERIALS TASK OF THE LOW COST
SOLAR ARRAY PROJECT (PHASE II)

Ninth Quarterly Report

1 October 1977 - 31 December 1977

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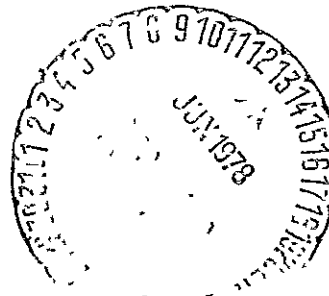
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TECHNICAL CONTENT STATEMENT

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NEW TECHNOLOGY

No new technology is reportable for the period covered by this report.

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1. SUMMARY

The objective of Phase II of this program is to investigate and define the effects of various processes, contaminants and process-contaminant interactions in the performance of terrestrial solar cells. The major effort this quarter has been in the areas of crystal growth and thermal processing, comparison of impurity effects in low and high resistivity silicon, modeling the behavior of p-type ingots containing Mo, and C and, quantitative analysis of bulk lifetime and junction degradation effects in contaminated solar cells.

In preparation for a series of gettering and annealing studies on impurity-doped silicon, we have measured the lifetime of uncontaminated silicon as a function of heat treatment temperature (200 to 1200°C). The change in reciprocal lifetime with reciprocal temperature follows essentially an Arrhenius behavior. If the process of recombination center generation is assumed thermally activated, then an energy of about 1.5 eV can be used phenomenologically to characterize the heat treatment effects above about 500°C. Below that temperature lifetime changes relatively little for fixed annealing time.

We measured the performance of solar cells fabricated on silicon web crystals grown from melts containing about 10^{18} cm^{-3} of Cr, Mn, Fe, Ni, Ti and V, respectively. There was no reduction in cell performance (compared to uncontaminated baseline cells) except for the impurities Ti and V; for the latter cell efficiency was reduced to about 75% of the baseline value. Using a recently developed first order model for impurity partitioning during web growth we estimate that for typical metals k_{eff} is about 2.5 times higher for web than for Czochralski growth. Combining the segregation coefficient data with our mathematical model for cell performance produces projected decreases in cell efficiency very close to those actually measured.

Thus on theoretical and experimental growths, we expect K_{eff} for web growth to be small ($\sim 10^{-5}$ to 10^{-4}) and that use of a solar grade feedstock may be feasible so long as crystal perfection is not adversely affected.

Solar cells made on 0.2 Ω -cm and 4 Ω -cm silicon containing Cr, Mn and Cu respectively show substantially the same efficiencies so long as the metal impurity content is comparable in each case. Thus, no synergism between effects due to boron and the impurities is evident. However, we do note considerably more scatter in the individual cell data for devices made on the low resistivity material.

Sufficient data are available for Mo, C, and P-doped ingots to develop an idea of cell performance degradation mechanisms. Mo essentially effects the devices through a reduction in minority carrier lifetime in a manner much like Cr and Ti. Carbon shows little effect on cell performance at concentrations just over 10^{17} cm^{-3} . However, excessive carbon seriously degrades crystal structure during growth. The behavior of P can be modeled using the same mathematical approach as for other impurities except that cell performance degradation involves a mobility rather than lifetime reduction. At $3 \times 10^{16} \text{ cm}^{-3}$ level cell performance declines hardly at all.

Deep level spectroscopy of metal-contaminated ingots has been employed to determine the level and density of recombination centers due to Ti, V, Ni and Cr. Generally the electrically active impurity concentration is close to or somewhat lower (Ti) than the metallurgically determined concentration. Detailed I-V analyses show that when Cu and Mn are present in a device, measured lifetime reduction is due only to Mn while Cu increases junction leakage. No synergism is evident. Iron degrades both bulk and junction properties.

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2. INTRODUCTION

The overall objective of this program is to determine how various processes, impurities and impurity-process interactions affect the performance of terrestrial silicon solar cells. The development of such data permit the definition of the tolerable impurity levels in a low-cost Solar Grade silicon, and also identify what processes mitigate or enhance the effects of impurities in silicon. This information can be employed in carrying out various cost-tradeoff analyses by both producers and users of Solar Grade material.

The bulk of the activity during this quarter falls into five categories: (1) measurement of the effect of heat treatment temperature and silicon cooling rate on minority carrier lifetime (the basis for subsequent impurity gettering and annealing experiments) (2) a comparison of impurity effects in low ($0.2\Omega\text{cm}$) and high resistivity ($4\Omega\text{cm}$) silicon (3) expansion of our capability to model and predict solar-cell performance in contaminated $\overline{\text{p}}$ -type silicon (4) quantitative analysis of bulk junction degradation due to impurities in silicon solar cells and (5) an assessment of impurity partitioning and solar cell performance in silicon ribbons produced by the dendritic web growth process.

3. TECHNICAL RESULTS

3.1 Silicon Ingot Preparation and Evaluation

Czochralski and Float-zoned silicon single crystal ingots infused with controlled amounts of metal contaminants are the primary test vehicles for our assessment of impurity effects in silicon. While the majority of effort to date has involved the preparation/evaluation of high resistivity (4.0 ohm-cm) p-type silicon primarily with transition elements, a substantial amount of n-type material and low resistivity p-type material has now been prepared. The concentration ranges investigated for 4.0 ohm-cm, p-type, 0.2 ohm-cm, p-type, and 1.5 ohm-cm, n-type ingots are summarized in Table 1. The choice of 0.2 Ω -cm, p-type material for investigation was made after evaluating the relative performance of cells made on material with resistivity ranging from 0.05 ohm-cm through 4.0 ohm-cm. In addition, multicrystalline, float zoned and multiply-doped ingots containing two or more of the impurities shown in Table 1 have been prepared. The crystal preparation and chemical analysis of the material has been described previously¹. We present below a tabulation of recent growth runs and highlights of the analytical activity. A compilation of the resistivity, etchpit density and analytical results for all ingots prepared so far appears in Appendix 7.1

Table 1. Impurity Matrix Under Investigation

Impurity Element	Approximate Concentration Range Investigated $\times 10^{15}$ atoms per cm^3 (a)		
	4 ohm-cm p-type	0.2 ohm-cm p-type	1.5 ohm-cm n-type
Aluminum	3 - 50**		3 - 50
Boron*			
Calcium	0.1		
Carbon	20 - 500 ⁺		
Chromium	0.1 - 1.1	0.5	1.0
Copper	0.4 - 60	2.3	2.5
Iron	0.02 - 1.5		1.0
Magnesium	0.003 - 0.03		
Manganese	0.01 - 1.3	0.7	2.0
Molybdenum	~0.06 - 0.3		
Nickel	0.4 - 4.0		2.3
Oxygen	500 - 1700 ⁺		
Phosphorus*	1.0 - 28		
Sodium			
Titanium	0.00036 - 0.36	0.2	0.36
Tantalum			
Vanadium	0.0004 - 0.4	0.4	0.4
Zinc ⁺	<0.001		
Zirconium	<0.015		<0.015

* Boron and phosphorus are electrically active impurities and therefore cause variations in resistivity when used as a secondary impurity.

** Uncertainty in exact range due to discrepancy between electrical and SSMS measurements.

⁺ Oxygen and carbon concentrations measured in 50 ingots doped with additional impurities. No effort yet to correlate effects if any.

a 1 ppm $\approx 5 \times 10^6$ atoms cm^{-3}

3.1.1 Ingot Growth

Twelve ingots were prepared this quarter using the Czochralski growth method and two using the floating zone method. Details of the crystal growth equipment and growth conditions employed for Czochralski growth have been described previously^{2,3}. Float zone crystal growth was conducted under vacuum with a coil speed of 15 cm/h. Ingots were prepared in support of all program tasks and included:

- 1 n-type doubly doped (1.5 ohm-cm)
- 2 p-type doubly doped low resistivity (0.2 ohm-cm)
- 2 p-type multiply doped (4 ohm-cm)
- 2 p-type doubly doped (4 ohm-cm)
- 2 p-type FZ baseline (4 ohm-cm)
- 1 p-type CZ baseline (4 ohm-cm)
- 2 p-type doubly doped (4 ohm-cm)-process studies
- 2 p-type doubly doped multicrystalline (4 ohm-cm)

Among the ingots two multicrystalline specimens were prepared, W-094-Mn-005 and W-102-Ti-006. Fine grain polycrystalline seeds were used for both ingots thus providing a relatively small grain size with a multitude of crystalline orientations. It would appear to be desirable to produce some large grain material in the future which would be representative of Czochralski grown material which is twinned out or lost structure due to oxide specs in the melt.

Ingots W-095-Mn-006(F) and W-096-Mn-007(S) were grown at rates of 15.25 cm/h and 1.9 cm/h respectively to determine if this range of growth rates could result in significantly different impurity concentrations hence differing solar cell performances. Structural breakdown of W-095 occurred earlier than that of W-096 as expected. Two copper/titanium doped ingots (W-100 and W-104) were prepared to verify the magnitude of previously observed synergistic effects associated with these impurities. Impurity concentrations in the two ingots differ by a factor of two.

3.1.2 Ingot evaluation

Up to date information on ingot resistivity, etch pit density, melt analysis and measured impurity concentrations (mass spectroscopy and activation analysis) are tabulated in Appendix 7.1 along with segregation coefficient data for the impurities of interest. Approximately thirty-two samples from various ingots between numbers W054 and W106 have been forwarded for irradiation and neutron activation analysis. The results of these efforts should be available for the next quarterly progress report. Good agreement exists between target concentrations and calculated values based on melt analysis. This has been the case throughout the program.

Spark source mass spectrographic analysis remains behind schedule. Several samples doped with chromium and manganese were analyzed this quarter. The exposures were quite uneven, i.e., line darkening on 300 and 30 nanocoulomb exposures but not the intermediate 100 nanocoulomb exposure. This places substantial uncertainty on impurity values measured for Ingots W-088, W-090, W-093, and W-094. Samples from these ingots have been prepared for neutron activation analysis and will undergo further SSMS analysis during the next quarter.

Odd numbered ingots were selected for carbon and oxygen determination. The results of these measurements are reported in Table 2. No significant variations are observed among the ingots produced this year nor between those produced this year and those produced during the first phase of the program. Neither carbon nor oxygen could be detected in float zoned Ingots W-099 and W-101. Due to free carrier absorption, infrared absorption cannot be used for carbon and oxygen determination in low resistivity ingots.

As in the past, we have utilized all analytical data to arrive at a best estimate of the impurity concentrations for all ingots under study. This data forms the basis for the modeling studies and other data correlations. A compilation of this information appears in Table 3.

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Table 2 Carbon and Oxygen Concentrations

<u>Ingot Number</u>	<u>Carbon Concentration</u> <u>$\times 10^{16}$ atoms/cm³</u>	<u>Oxygen Concentration</u> <u>$\times 10^{16}$ atoms/cm³</u>
W-055-Cu-004	11.3	118
W*-057-00-000	**	**
W*-059-00-000	**	**
W-061-Cr/Ti-001	<2	181
W-063-N/Cu-001	4.4	164
W-065-N/Ti-001	<2	176
W-067-Cr/Mn/Ti-001	<2	226
W-069-Fe-004	<2	146
W-071-00-000	7.6	115
W-073-Cr/Mn/Ni/Ti/V-001	4.2	145
W-075-Ti/V-002	11.6	194
W-077-Mo-001	2.5	134
W-079-00-000	<2	157
W-081-N/Ni-001	5	216
W-083-N/V-001	5.5	136
W-085-N/Zr-001	<2	96
W-087-Ca-001	4.5	69
W*-089-Cu-001	**	**
W-091-Cr/Mn-002	20	111
W-093-Mn-004	7	161
W-095-Mn-005	4.2	151
W-097-00-000	13.2	142
W-099-FZ-001	<2	<5
W-101-FZ-002	<2	<5
W*-103-Ti-001	**	**
W*-105-V-001	**	**

** Due to free carrier absorption infrared methods cannot be used for carbon and oxygen determination in these samples.

Table 3 Best Estimate of Impurity Concentration

<u>Ingot Number</u>	<u>Impurity Concentration</u> <u>(10¹⁵ atoms/cm³)</u>	
W-054-00-000	N/A	--
W-055-Cu-004	0.05	(<1)
W-056-Cu-005	65	(70)
W-057-00-000	N/A	--
W*-058-00-000	N/A	--
W*-059-00-000	N/A	--
W-060-00-000	N/A	--
W-061-Cr/Ti-001	Cr: 1.0 Ti: 0.02	(1.0) (<1)
W-062-N/Cu-001	2.0	(2.0)
W-063-N/Cr-001	0.8	(1.0)
W-064-N/Mn-001	2.0	(2.0)
W-065-N/Ti-001	0.35	(0.75)
W-066-Ti-005	0.06	(<0.2)
W-067-Cr/Mn/Ti-001	Cr: 0.4 Mn: 0.5 Ti: 0.006	(0.3) (0.7) (<0.2)
W-068-Cr-004	1.0	(1.0)
W-069-Fe-004	1.0	(<1.5)
W-070-Al-003**	50	(100) (10)**
W-071-00-000	N/A	--
W-072-Cr-005	0.4	(0.28)
W-073-Cr/Mn/Ni/Ti/V-001	Cr: 0.4 Mn: 0.5 Ni: 2.0 Ti: 0.004 V: 0.004	(0.28) (0.80) (<2.0) (<0.35) (<0.35)
W-074-Cr/Mn/Ni/Ti/V-001	Cr: 0.08 Mn: 0.08 Ni: 0.5 Ti: 0.0006 V: 0.0006	(<0.25) (<0.25) (<2.0) (<0.25) (<0.25)
W-075-Ti/V-002	Ti: 0.1 V: 0.1	(<0.25) (<0.25)
W-076-Poly-002	N/A	--

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Table 3 Best Estimate of Impurity Concentration (Cont.)

<u>Ingot Number</u>	<u>Impurity Concentration</u> (10^{15} atoms/cm ³)	
W-077-Mo-001	0.1	(<0.3)
W-078-00-000	N/A	--
W-079-00-000	N/A	--
W-080-Ph-001**	0.7	(0.7)**
W-081-N/Ni-001	1.7	(<2.0)
W-082-N/V-001	0.4	(0.85)
W-083-N/Fe-001	1.0	(<1.5)
W-084-N/Al-001**	50	(40) (4)**
W-085-N/Zr-001	<0.015	<0.3
W-086-C-001	400	(200-300)
W-087-Ca-001	?	?
W*-088-Cr-001	0.5	(3.3)
W*-089-Cu-001	2.0	Incomp.
W*-090-Mn-001	0.7	(2.75)
W-091-Cr/Mn-002	0.5/0.3	(1.0/2.75)
W-092-Ph-002**	28	(27-30)**
W-093-Mn-004	0.66	(2.75)
W-094-Mn-005 (Poly)	0.9	(2.75)
W-095-Mn-006 (F)	0.5	Incomp.
W-096-Mn-007 (S)	0.65	Incomp.
W-097-00-000	N/A	--
W-098-Mo-002	<0.1	(<0.3)
W-099-FZ-001	N/A	--
W-100-Cu/Ti-002	1.0 0.06	Incomp.
W-101-FZ-002	N/A	--
W-102-Ti-006 (Poly)	0.2	Incomp.
W*-103-Ti-001	0.3	Incomp.
W-104-Cu/Ti-003	2.0 0.25	Incomp.
W*-105-V-001	0.4	Incomp.
W-106-N/Al-002**	6.6	(0.7)**

**

Double asterisks indicated impurity concentrations determined by electrical measurements.

3.2 Processing Studies

Both crystal growth and subsequent thermal processing of silicon can influence the distribution and electrical activity of the impurities initially present in the silicon feedstock. It is fairly well known, for example, that the degree of impurity segregation during crystal growth is influenced strongly by growth rate, among other parameters. Gettering is one of the several thermal processes that can subsequently alter the effects of impurities in silicon. As part of this program, we undertook to evaluate the effects of growth rate -(for both Czochralski and ribbon techniques) on the properties of the silicon produced. Gettering and annealing experiments form a second part of the process study. Recent results for both activities are reported below.

3.2.1 Crystal Processing: Impurity Behavior during Silicon Web Growth

Ribbon or sheet forms of silicon must be produced at large area throughout rates to become cost competitive as solar cell substrates. Ribbon growth rates, in fact, fall in the range 50 to 600cm/hr, far in excess of those commonly practiced for conventional Czochralski pulling. For this reason it is often tacitly assumed that impurity incorporation will be significantly greater in ribbon crystals than in silicon ingots. Should this prove true, then less pure "solar" grades of silicon would be much less attractive as cheap feedstocks for ribbon crystal growth. To test this possibility, we recently evaluated solar cells fabricated on silicon dendritic web crystals purposely contaminated with controlled amounts of impurities. Silicon web is one of several forms of ribbon silicon which are candidate substrates for low cost solar cells.

When this study was initiated, the effective segregation coefficients, k_{eff} (web), for web growth were undetermined, but postulated to be one or two orders of magnitude larger than the equilibrium value k_0 . Thus, silicon webs 0.2 to 0.3mm thick were grown at 1 cm/min from melts doped with 1 to $3 \times 10^{18} \text{ cm}^{-3}$ of Mn, Fe, Cr, Ni, Ti, or V metal. At these concentrations, we expected sufficient impurity incorporation that solar cell performance would be noticeably affected.

The webs, typically 15mm wide as grown, were scribed into 25mm lengths and fabricated by the standard process we use for Czochralski material into 5 x 20 mm solar cells. The performance of devices made on the contaminated material was compared directly to cells processed concurrently from webs containing no added transition metal. The efficiency of the base-line web cells was approximately 12.5% with AR coatings but no back surface field.

The results of these experiments, Table 4, indicate that no measurable degradation in cell performance is evident save for the impurities Ti and V - elements which drastically reduce minority carrier lifetime.

Table 4 Relative Solar Cell Efficiency for Devices Fabricated on Contaminated Silicon Webs

<u>Impurity</u>	<u>Web I.D.</u>	Target Melt Concentration	Relative Cell Efficiency*
		$(10^{18} \text{ cm}^{-3})$	$(\eta/\eta_{\text{Base}})$
Cr	061	1.6	1.03
Mn	065	2.6	1.07
Fe	069	1.3	1.01
V	074	1.5	0.80
Ti	083	2.2	0.73
Ni	084	1.1	1.01

The implication of the data is that k_{eff} for web growth is considerably smaller than originally supposed. For example, comparison of the relative efficiencies in Table 4 with the previously determined relationships between silicon impurity content and cell performance, e.g. Figure 9, suggests that the solid impurity content in the webs must be $< 10^{14} \text{ cm}^{-3}$ so that $k_{\text{eff}} < 10^{-4}$. Conventional analytical methods are insufficiently sensitive to measure concentrations so low in these thin webs.

* Solar cell data represent averages of 8 to 15 cells.

Because of these analytical difficulties and the need to develop a better understanding of impurity partitioning during ribbon solidification, we carried out a series of experiments in which electrically active metal impurities having small k_o were used to mimic transition metal behavior. The salient results of the study which was conducted on an internally-funded Westinghouse program are outlined below; the details appear in Appendix 7.2.

The growing web rejects impurities which diffuse through the meniscus liquid and then mix with the bulk silicon melt. We assumed that the meniscus could be approximated as a cylindrical wedge, that solute diffused first through a stagnant boundary layer of thickness δ , and that mixing on the bulk liquid was complete. The solution to the diffusion problem for $k < 1$; the case for most metals in silicon, yielded

$$\frac{k_{\text{eff}}(\text{web})}{k_o} = 1 + \frac{v_o t}{2D \sin \theta} \quad (\text{Eq. 3.1})$$

where v_o is the web growth velocity, t the web thickness, D the liquid diffusivity and θ the wedge half angle. With literature data for k_o and D and experimental values of v_o and t , the equation predicts $3 < \frac{k_{\text{eff}}(\text{web})}{k_o} < 5$ for the impurities Al, Ga and In. The measured values

of $\frac{k_{\text{eff}}(\text{web})}{k_o}$ deduced from the resistivities of the Al, Ga and In-doped web specimens was about a factor of 2 to 3 lower than those predicted by the model.

The key point is that both on experimental and theoretical grounds we should expect segregation coefficients for metals in web to be small and not too much larger numerically than those for Czochralski pulling.

Using Equation 3.1, and the conditions characterizing the web experiments in Table 4 ($v_0 = .0167$ cm/sec, $t = 0.3$ cm, $D \approx 5 \times 10^{-4}$ cm/sec) we estimate $k_{\text{eff}}(\text{web}) = 2.5 k_0 \approx 2.5 k_{\text{eff}}(\text{Czo.})$. From the values of $k_{\text{eff}}(\text{Czo})$ tabulated in Appendix 7.1, we calculate $k_{\text{eff}}(\text{web})$ and the impurity concentration in the webs themselves via Table 5.

By using the mathematical model describing the variation in cell performance with impurity content (Ref 1 and Section 3.5) we can project the value of η/η_B for each web in the table and compare it to the measured data. In each case the values agree within the expected errors involved in the calculation. Clearly, at least for silicon web, the segregation coefficients for the growth process are sufficiently small that considerable purification can occur. So long as the crystal structure is not perturbed feedstock impurity concentrations as high as 10^{18} cm^{-3} can be tolerated without reducing cell efficiency below 10% (the values observed when Ti and V were incorporated).

3.2.2 Thermal Processing: Effects of Annealing Temperature and Cooling Rate on Silicon Lifetime

Studies have been partially completed on the effects of high temperature cycling on recombination lifetime. The work described below was performed on high lifetime silicon prior to studying gettering and annealing of impurity doped material. These background experiments are required so that changes in lifetime due to gettering, for example, can be clearly distinguished from those induced by the high temperature treatment itself or by excessively high cooling rates. This is especially important if the optimum gettering and annealing temperatures are found to be greater than those normally used to form the active p-n junction.

At elevated temperatures the thermal agitation of the silicon lattice can cause the generation of point defects, which may be momentarily quenched into the material during rapid cooling. These quenched-in defects are potential sources of trap levels within the band gap by which carrier recombination can take place.

Table 5 Comparison of Measured and Predicted Web Cell Performance

Impurity	$k_{\text{eff}}(\text{Czo})$	$k_{\text{eff}}(\text{web})$	$C_1 (10^{18} \text{ cm}^{-3})$	$C_s (10^{13} \text{ cm}^{-3})$	$\eta/\eta_B(\text{meas})$	$\eta/\eta_B(\text{predicted})$
Cr	$1.1(10^{-5})$	$2.75(10^{-5})$	1.6	4.4	1.03	0.965
Mn	$1.3(10^{-5})$	$3.25(10^{-5})$	2.6	8.5	1.07	0.965
Fe	$6.4(10^{-6})$	$1.6 (10^{-5})$	1.3	2.1	1.01	0.966
Ni	$3.2(10^{-5})$	$8(10^{-5})$	1.1	8.8	1.01	0.980
Ti	$3.6(10^{-6})$	$9(10^{-6})$	2.2	1.9	0.73	0.765
V	$4(10^{-6})$	$1(10^{-5})$	1.5	1.5	0.80	0.785

We would expect the number of traps, N_t to increase with increasing temperature and increasing cooling rate, dT/dt . Maximum trap concentration should occur when the silicon is rapidly cooled from a quench temperature, T_q . Fig. 1 depicts the results of such an experiment. The lifetime of thick ($2d=0.113$ cm) specimens from baseline ingot W078 was measured before and after the heat treatment. The initial lifetimes ranged from 46.4 to 59.0 μsec or an average value of 52 μsec . The specimens were maintained at the quench temperature, T_q for 15 minutes in dry N_2 and then pulled rapidly ($\approx 1\text{s}$) from the furnace. The results, Fig. 1, are consistent with the hypothesis that the number of defects present at T_q can be described by Boltzmann's statistics. In the event that such a simple model is valid, the activation energy for such defect formation might be determined from an Arrhenius plot. The trap density, N_t will be proportional to $1/\tau_r$ if all the traps are identical (constant capture cross section). A plot of $1/\tau_r$ vs $1/T$ is shown in Fig. 2. The activation energy at higher temperatures approaches a value of 1.48 eV. Although it is not yet clear what defect or defect complexes are associated with this energy, the value can be used phenomenologically to characterize the quenching results and to model the lifetime behavior.

Once the effect of processing temperature on lifetime is characterized, it then becomes necessary to define what cooling rate from the process temperature can be safely employed without lifetime degradation. The primary methods used to control cooling rate are programmed cooling of the furnace itself and mechanical pullers which drive at a slow and precise speed. Mechanical pullers produce a cooling rate

$$\frac{dT}{dt} = \frac{dT}{dx} \cdot \frac{dx}{dt} \quad (\text{Eq. 3.2})$$

where dT/dx is the temperature gradient of the furnace and dx/dt is the withdrawal velocity.

Curve 693453-A

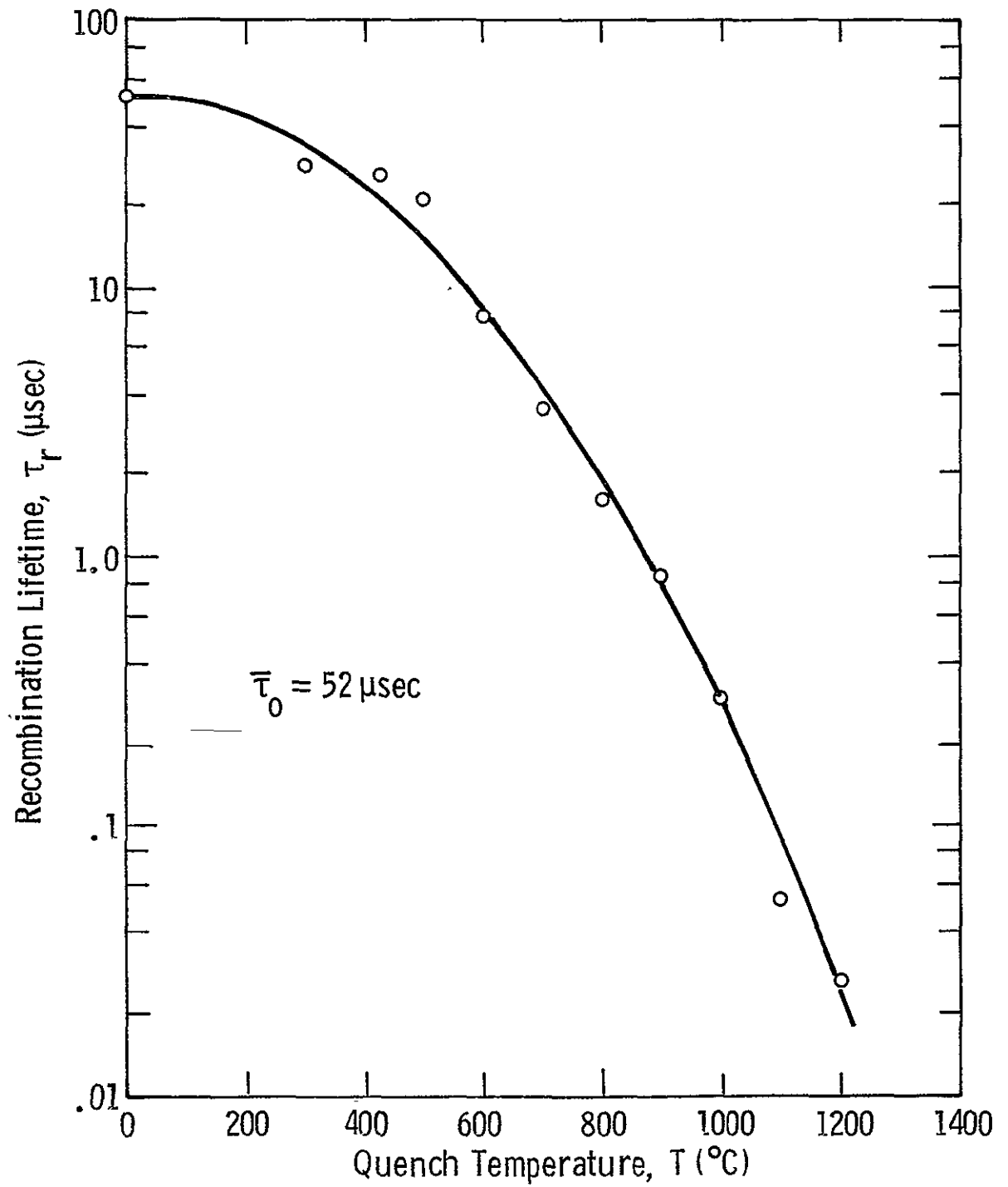


Fig. 1 - Effect of quenching from a high temperature on the recombination lifetime of p-type Qz silicon.

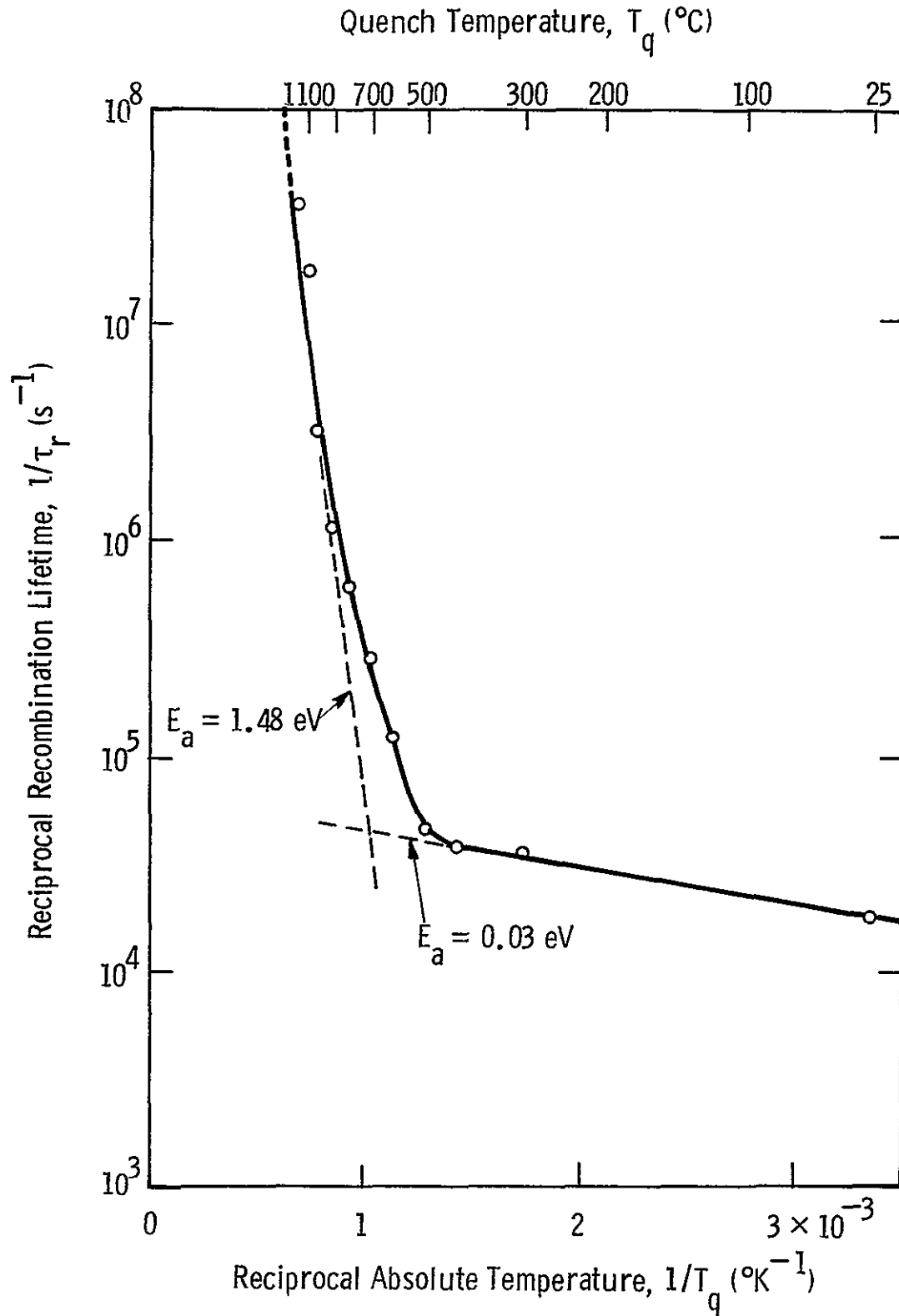


Fig. 2 - Arrhenius plot for generation of recombination centers in p type silicon

The temperature gradient of a furnace is generally a variable with distance from the centerline of the furnace, and dx/dt must be a corresponding variable in order to maintain a constant cooling rate.

Mechanical pullers are also limited in the range of pull velocity unless elaborate change gears are added. A speed range of 20:1 is normal. Programmed furnace cooling techniques are only possible up to some maximum value which depends on the ratio of the heat losses to the thermal mass of the heated section. The heat losses are in turn a function of temperature and the maximum cooling rate decreases with temperature.

Fig. 3 indicates the fall of temperature with time resulting when the furnace power is turned off. The decrease in radiative cooling with temperature is primarily responsible for the upward curvature. The cooling rate, obtained by differentiating the curve in Fig. 3, is illustrated in Fig. 4. The limitations of programmed furnace cooling are obvious. Rates in excess of $\sim 1^{\circ}\text{C}/\text{min}$ are non-linear and cooling rates in excess of $\sim 10^{\circ}\text{C}/\text{min}$ are impossible to achieve. A study of recombination lifetime retention vs cooling rate was therefore initiated using both types of cooling techniques in order to span a wide range of dT/dt .

The mechanical puller available was capable of achieving velocities ranging from 0.2 to 70cm/min. The furnace gradient ranged from 2.5 to $45^{\circ}\text{C}/\text{cm}$. The mechanical puller was therefore able to produce constant cooling rates ranging from 10 to $400^{\circ}\text{C}/\text{min}$. Cooling rates below $10^{\circ}\text{C}/\text{min}$ were produced by furnace programming as discussed earlier. Again, thick ($2d=0.113\text{cm}$) specimens from baseline ingot W078 were employed. The average lifetime of the material prior to diffusion was $53 \pm 6 \mu\text{sec}$. The specimens were inserted into the furnace, maintained at 1000°C for 15 minutes in flowing N_2 (500cc/min), and then cooled at rates varying from 1 to $400^{\circ}\text{C}/\text{min}$. The specimens were remetallized, etched and measured photoconductively for recombination lifetime.

The results of the experiment (Figure 5) show considerable scatter and a large discrepancy with the behavior expected (the dashed curve is based in part in previous experience with power semiconductor devices).

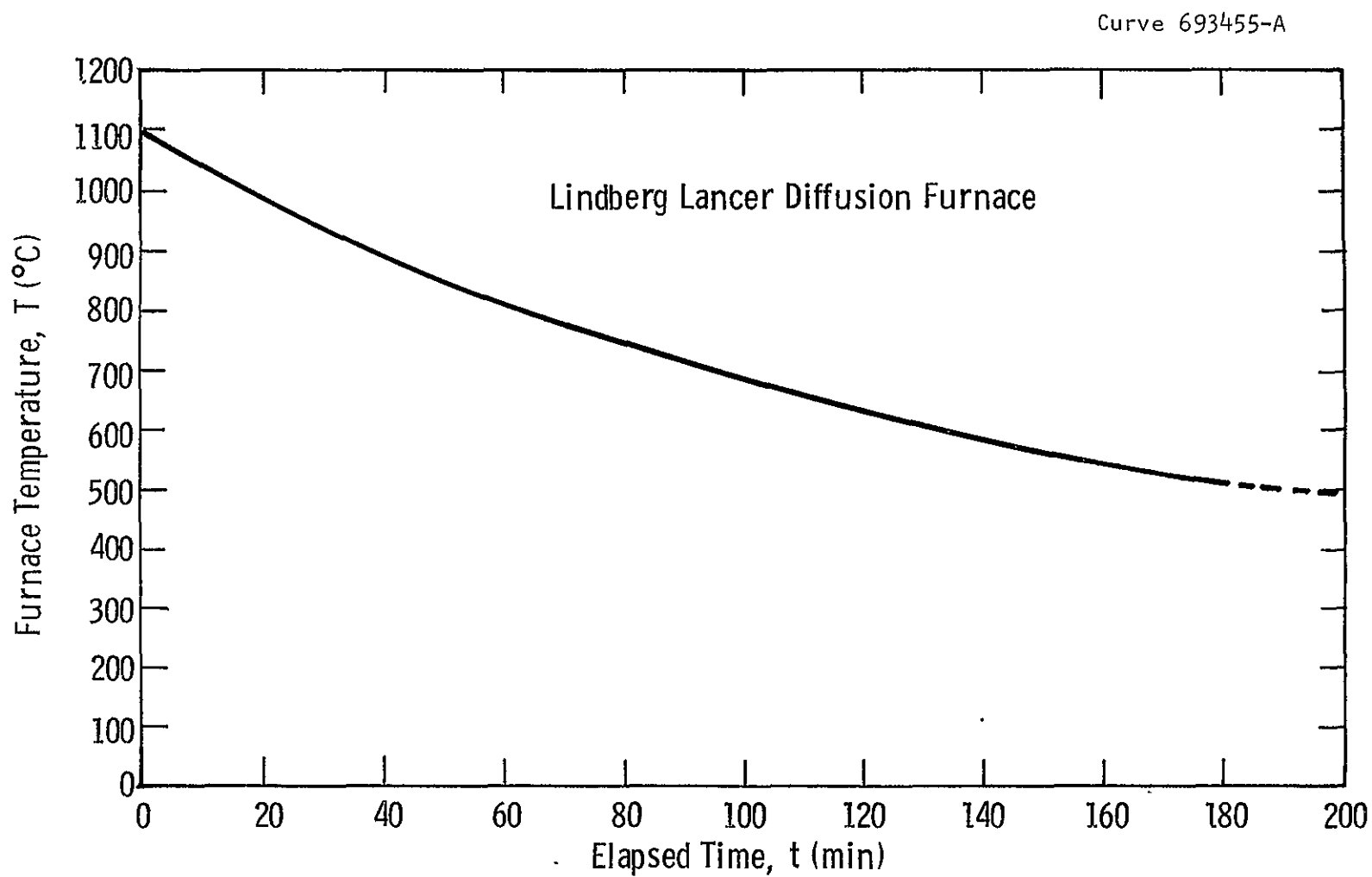


Fig. 3 - Decay in diffusion furnace temperature due to natural cooling

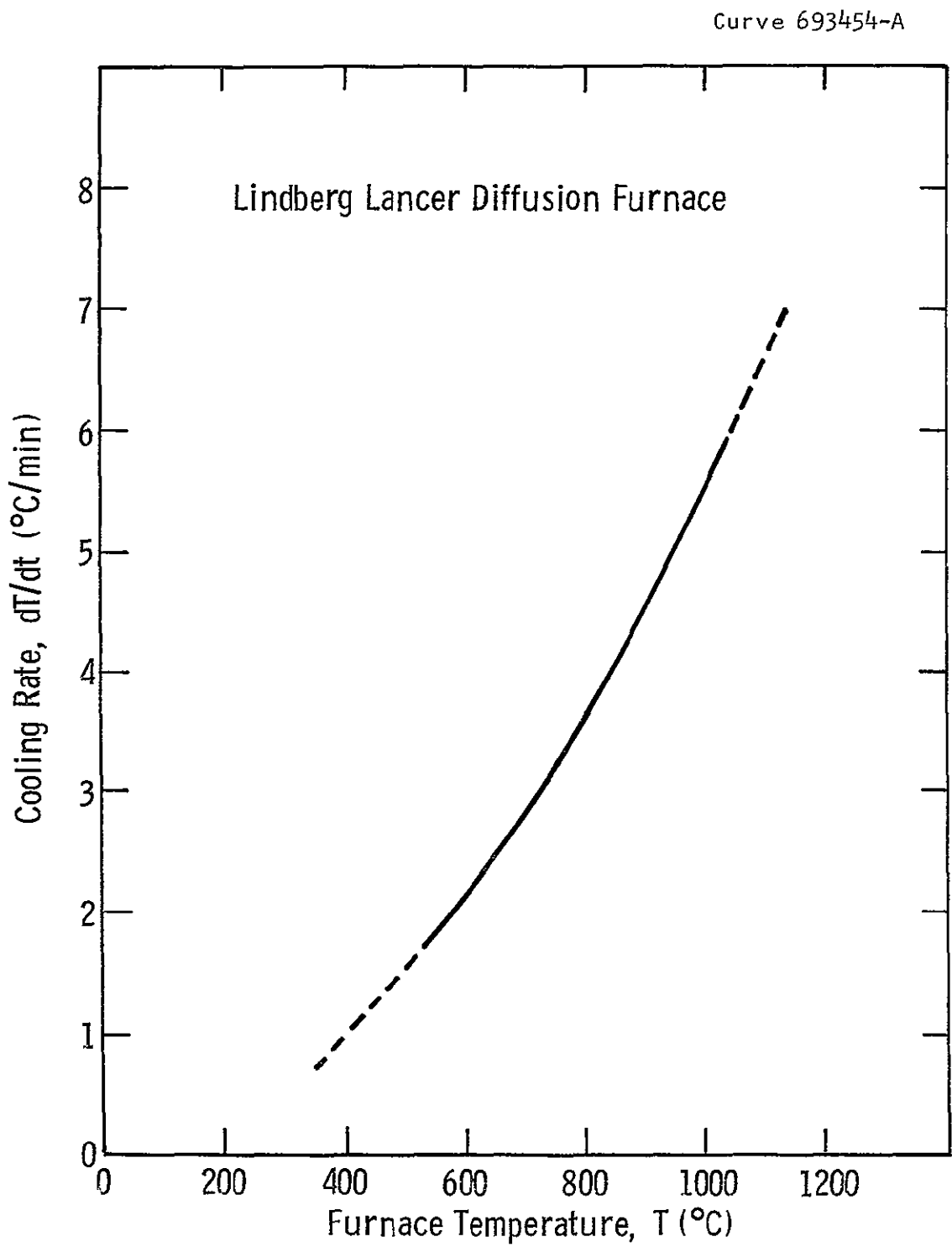


Fig. 4 - Natural cooling rate for a typical diffusion furnace

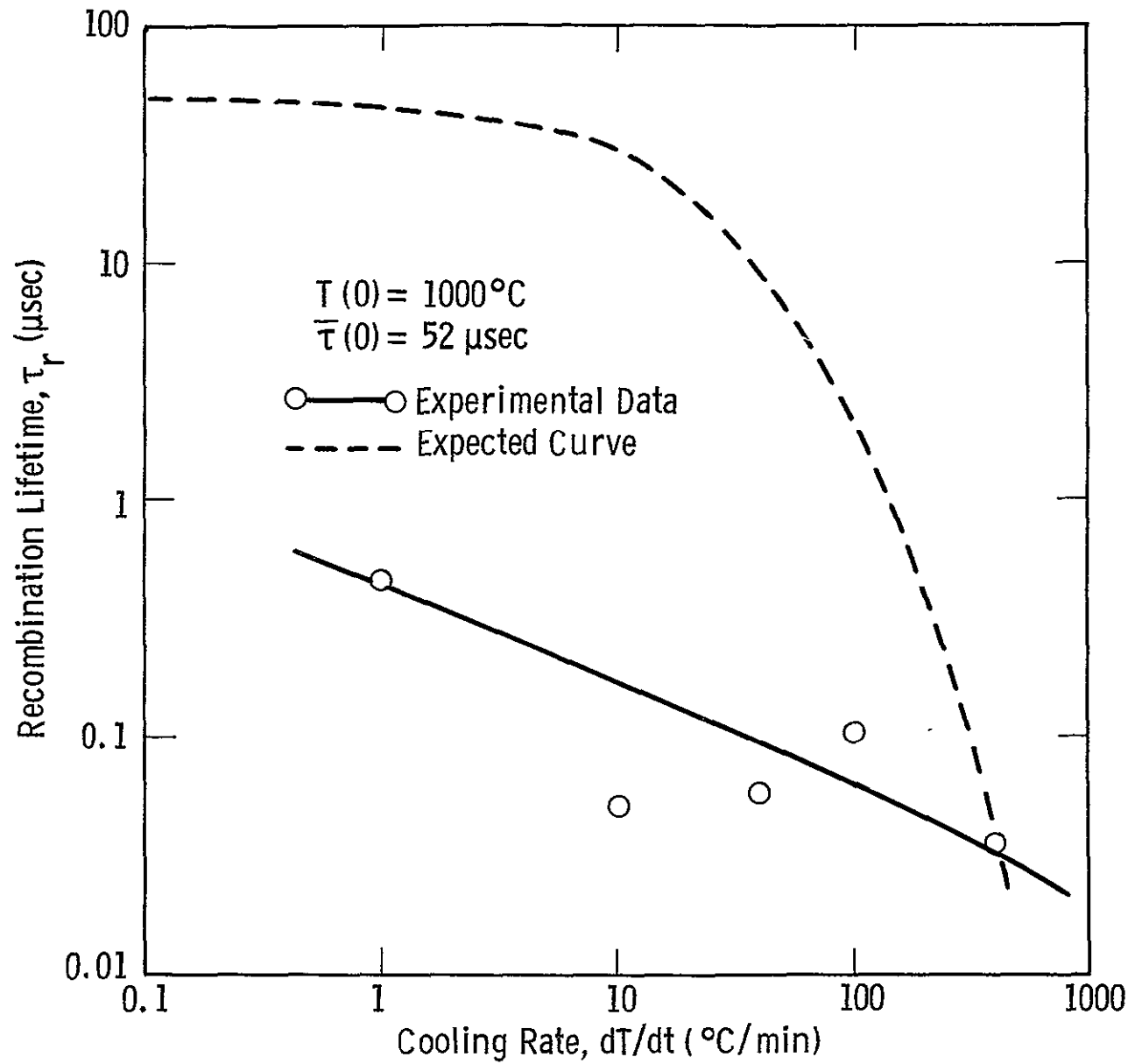


Fig. 5 - Effect of cooling rate on recombination lifetime

While the trend of the data are correct, this first experiment clearly was compromised. A review of the technique employed to remove the metallization strips necessary for initial lifetime measurements on each sample suggests that surface contamination occurred during cleaning and degraded the lifetime during subsequent heat treatment. The experiment is being rerun along with similar measurements at 1150 and 850°C.

The experimental results do indicate however, the value of precise PCD measurements as a tool for assessing the results of processing experiments. Moreover, the systematic gathering of data in quench temperature and cooling rate prior to gettering experiments is clearly required. Otherwise contamination effects like those we encountered could, if undetected, completely mask the beneficial effects of gettering and annealing processes themselves.

3.3 Combined Effects of Boron and Metal Impurities on Solar-Cell Performance

Boron is a common contaminant in the raw materials from which silicon is produced and is very likely to be present at high levels in some "solar grade" materials. The purpose of this task is to assess whether the combined effects of boron and metal contaminants produce solar cell performance degradation in excess of that do to the boron or metal alone. In a preliminary study we evaluated the variation of solar cell parameters with boron content (resistivities from 0.05 to 50 Ω cm) in the absence of intentional contamination³. Cell efficiency went through a broad maximum at 0.2 to 0.4 Ω cm resistivity and 0.2 Ω cm was chosen for the impurity investigation.

The average data from the first three metal doped ingots W*088-Cr-001, W*089-Cu-001 and W*090-Mn-001 are compiled in Table 6 with data from comparable 4 Ω cm ingots doped with approximately the same amounts of the metal impurities. The raw I-V data appear in Appendix 7.3.

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Table 6 Comparison of Low and High Resistivity Ingots piped with Cr, Cu and Mn

<u>Contaminant</u>	<u>Concentration(10^{15} cm^{-3})</u>	<u>Resistivity(p-type)</u>	<u>Relative Cell Efficiency (η/η_o)*</u>
Cr	0.5	0.2	0.89
Cr	0.4	4.0	0.83
Cu	2.0	0.2	1.02
Cu	1.5	4.0	1.0
Mn	0.7	0.2	0.83
Mn	0.7	4.0	0.86

* η_o - The efficiency of an uncontaminated baseline device typically 10% without AR coating

In general, there is a fairly close parallel between the two sets of data indicating that little synergistic behavior occurs and that most of the degradation in performance is due to lifetime reduction by the metal contaminant. The cell data for the low resistivity material, Appendix 7.3, does show considerably more scatter than usually encountered for high resistivity material processed by our usual method. This suggests that other effects, such as precipitation, may contribute in a random fashion to reduce cell output (see, e.g. Section 3.4.3)

3.4 Quantitative Analysis of Impurity Effects in Silicon and Silicon Solar Cells

3.4.1 Recombination Lifetime Measurements

3.4.1.1 Equipment Calibration for n-type silicon

Calibration of the laser-excited PCD lifetime equipment for measurement of p-type silicon was previously reported.⁴ The surface recombination velocity for minority carriers in p-type and n-type silicon should be different and the bulk lifetimes are expected to shift for a given trap level. We recently determined the surface recombination velocity for n-type silicon using the same technique developed for the p-type material.⁴ Thick wafers (1.11mm) cut from baseline ingot W079-00-000 were used for these measurements. The resistivity of the wafers was 2.21 ohm-cm and the diffusivity D_p in the n-type samples calculated from Einstein's relationship and Conwell's mobility curves⁵ was $11.74 \text{ cm}^2/\text{s}$.

Figure 6 illustrates how the uncorrected or effective lifetime, τ_r' for such a sample varies as the sample thickness is reduced by lapping and etching. The effect of higher modes on the data was taken into consideration by obtaining the average time constant between the $\frac{1}{4}$ and $\frac{1}{8}$ points of the maximum oscilloscope amplitude.⁴ Greater care was used to minimize the effects of higher modes in this calibration of n type material than in the previous work on p-type silicon. Thus, we expect that the data for thin specimens will be considerably more accurate.

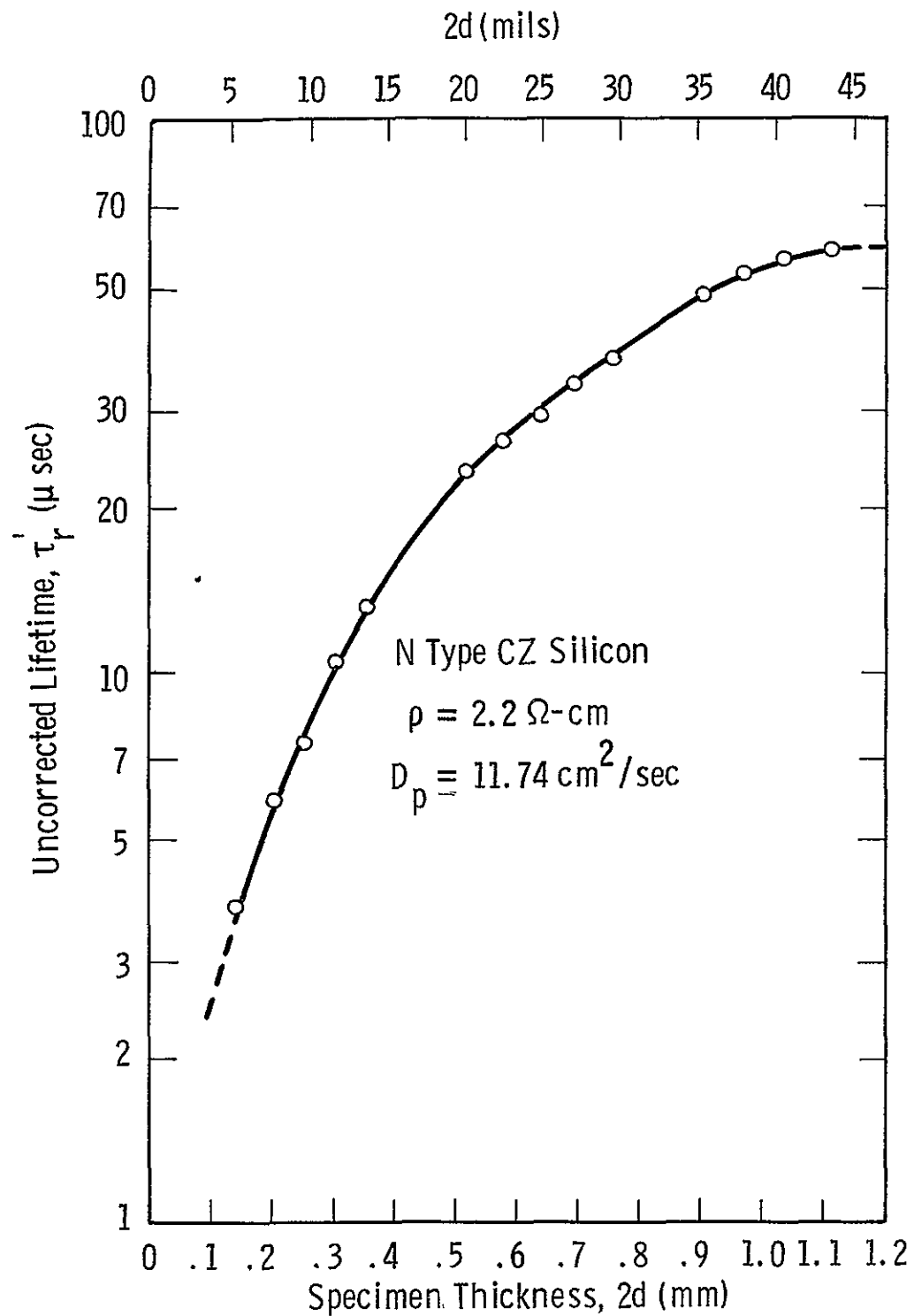


Figure 6 - Experimental data to be used in mathematically determining the surface recombination velocity, s , on n type silicon.

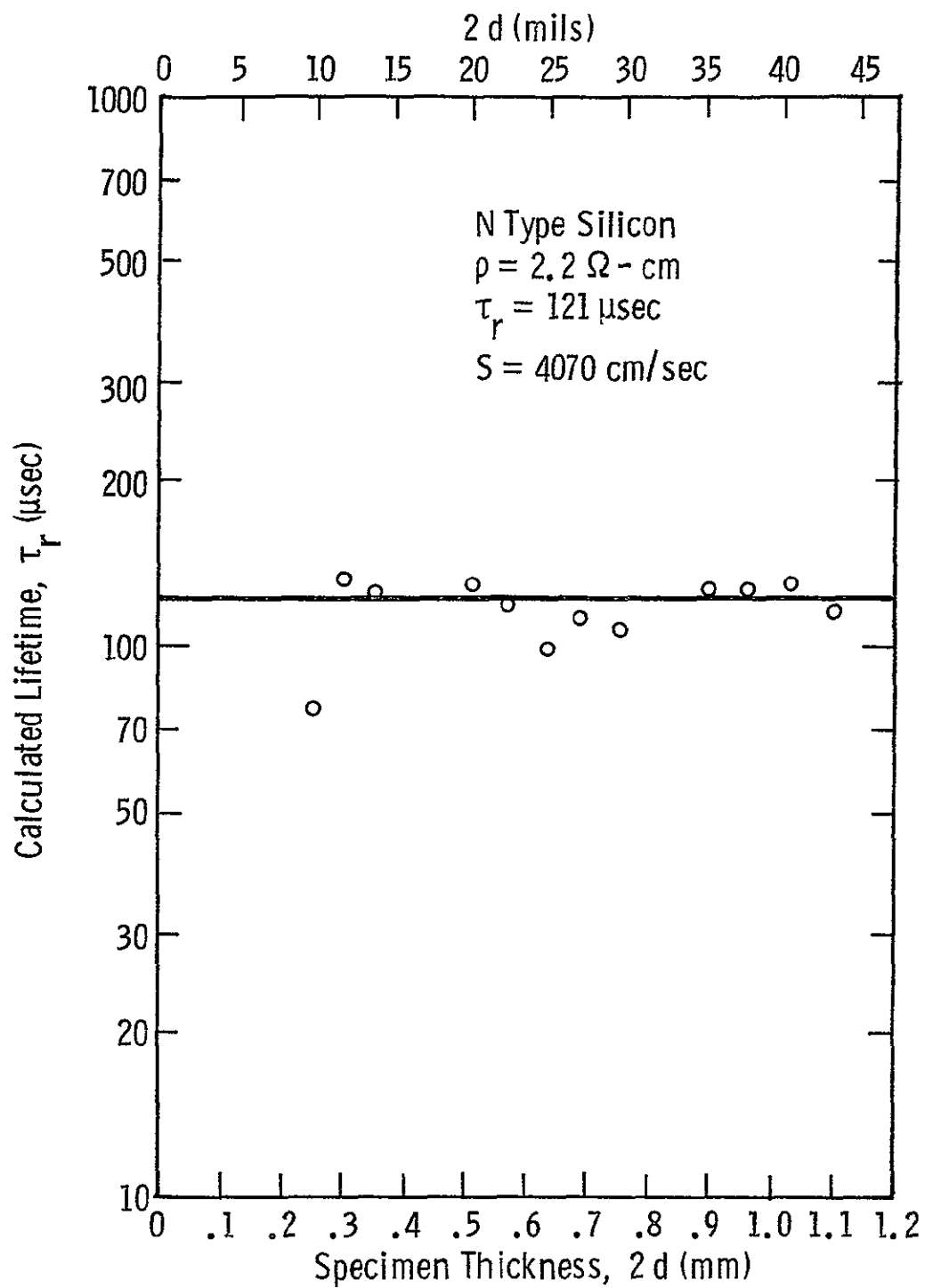


Figure 7 - Correctly chosen value of surface recombination velocity yields a constant lifetime as the specimen thickness is varied.

Fig. 7 shows the bulk lifetime, γ_r , calculated from the raw data, Fig. 6, when the surface recombination velocity is assigned a value of 4070 cm/s. The optimum value of 4070 cm/s is uniquely defined as the value of s necessary to achieve zero slope from linear regression of the calculated values of bulk lifetime. The corresponding intercept on the ordinate axis is 121 μ sec and is therefore the true bulk lifetime of this specimen. The standard deviation for the eleven readings taken on the same specimen is 10.24 or a probable error of 6.91 μ sec (5.7%). The data in Fig. 7 indicate that accurate lifetime measurements can be made on specimens as thin as 0.0254mm (10 mils). The diffusion length L_p for this sample is equal to 0.038 cm.

The previously established requirement that $(1/\gamma_r)/(1/r_{ooo})$ be equal to or greater than 1.0 for p-type silicon⁴ will now be examined for n-type silicon. For simplicity the term bulk rate, R_b will be used for $1/\gamma_r$ and the term surface rate, R_s will be used for $1/r_{ooo}$. The surface rate, R_s is well approximated in this case by the simplified equation

$$R_s = D_p \left(\frac{\xi_o}{d} \right)^2 \quad (\text{Eq. 3.3})$$

$$\text{where } sd/D_p = \xi_o \tan \xi_o \text{ and } 0 \leq \xi_o \leq \pi/2$$

Since the thickness, $2d$ is much less than the width ($2w=0.5\text{cm}$) or the length ($2l=1\text{cm}$). Fig. 8 shows a plot of the bulk lifetime necessary to achieve two values of R_b/R_s as a function of specimen thickness. The abscissa corresponding to $\gamma_r = 121 \mu\text{sec}$, and $R_b/R_s = 0.1$ is 0.32mm (12.6 mils). Accurate lifetime measurements were in fact performed on wafers as thin as 0.305 mm. This result is predicted in Blakemore and Nomura's study of transverse modes,⁶ and is a direct result of using the $1/4$ and $1/8$ points of the initial ($t=0$) oscilloscope amplitude. The $R_b/R_s=0.1$ curve in Fig. 8 may therefore be used to determine the minimum specimen thickness required to accurately measure any specified lifetime, γ_r .

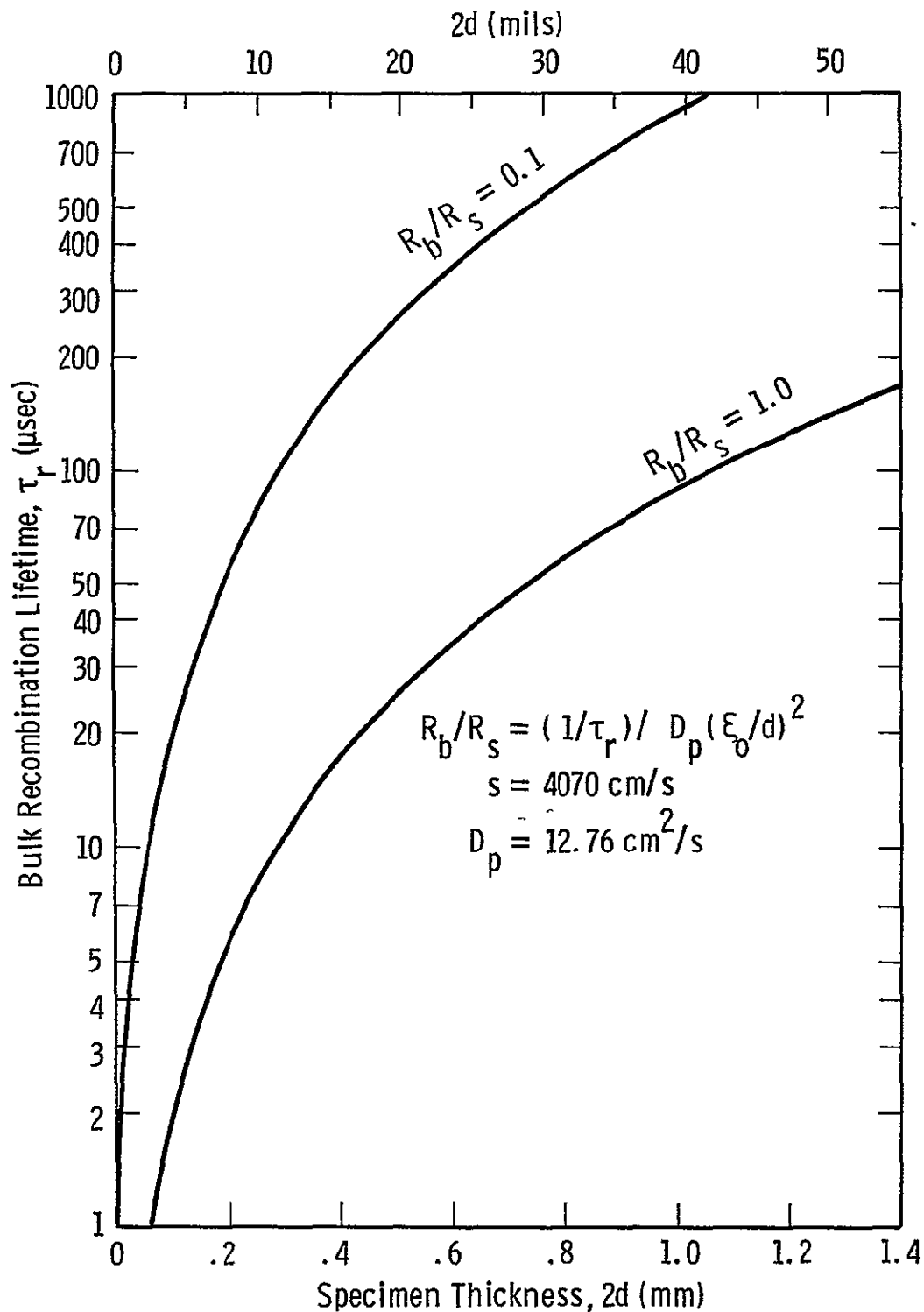


Fig. 8 - Specimen thickness necessary to achieve a desired ratio of bulk rate, R_b to surface rate, R_s as a function of specimen bulk recombination lifetime for PCD measurements on N-type silicon

3.4.1.2 Recombination Lifetime for Impurity-doped Ingots

The PCD lifetime measurement equipment is now completely calibrated for use on both n or p type silicon and systematic studies of processing effects on recombination lifetime of impurity doped silicon are being performed (see Section 3.2). The equipment is also currently being used to measure the lifetime of wafers from each ingot before and after processing into complete solar cells. A summary of this data for ingots W053 through W092 is given in Table 7.

3.4.2 I-V Analysis of Impurity Doped Solar Cells

3.4.2.1 Doubly-Doped Cells

In the previous report⁴ we outlined a detailed procedure for obtaining transformed I-V curves from measured dark solar cell I-V data. We also showed how to extract important cell parameters like series resistance (R_s), shunt-resistance (R_{sh}), reverse saturation current I_0 -sub lifetime (γ) and junction excess current (I_j , I_{o2} , n) from the I-V data. Since then detailed I-V analyses have been performed on several impurity-doped solar cells. This has provided a clearer insight into the effects of impurities on cell performance and also helped in understanding why some impurities like iron do not conform properly to the assumptions of the mathematical model.

In general, we have found that the impurities used in this study do not influence the series or shunt resistance sufficiently to account for any change in the cell performance. The impurities influence the solar cells either by altering the bulk lifetime or the junction excess current. Bulk currents (I_B , $V > 0.5$ volts) on the transformed I-V curves are quite reproducible and can be extrapolated to calculate I_0 , or γ without appreciable error. Unlike I_B , the junction excess current (I_j , $V < 0.4$ volts) shows appreciable scatter is very sensitive to processing steps such as sintering and cooling rate. Thus the junction excess currents shown on the transformed I-V curves represent the average, not absolute, behavior.

Table 7
RECOMBINATION LIFETIME MEASURED BY PHOTOCONDUCTIVE-DECAY METHOD
(Q-SWITCHED Nd:YAG Laser Excitation)

Ingot Identification	Lifetime (As-Grown)		Lifetime (Diffused)	
	τ (μsec)	σ (Note 1)	τ (μsec)	σ (Note 1)
W053-00-00	*6.6	0.1 (2)	---	--
W054-0000	*6.3	0.4 (2)	---	--
W055-Cu004	*6.2	0.1 (2)	*7.8	0.6 (2)
W056-Cu005	*6.7	0.3 (2)	*5.6	1.7 (4)
W057-00-000	1.84	- (1)	*4.6	0.7 (2)
W058-00-000	1.76	0.94(2)	1.78	0.01(2)
W059-00-000	Note 2	-	Note 2	--
W060-N00-000	11.45	0.24(3)	15.67	1.79(4)
W061-Cr/Ti-001	-	-	0.60	0.09(2)
W062-N/Cu-001	13.62	0.58(2)	12.11	2.01(2)
W063-N/Cr-001	1.67	0.11(2)	0.77	0.09(4)
W064-N/Mn-001	-	-	7.64	1.63(5)
W065-N/Ti-001	-	-	0.34	0.21(4)
W066-Ti005	0.49	0.0 (2)	0.73	0.0 (2)
W067-Cr /Mn/Ti-001	-	-	0.75	0.2 (2)
W068-Cr-004	0.03	0.00(2)	0.85	0.1 (2)
W069-Fe-004	0.04	0.01(2)	1.80	0.3 (2)
W070-Al-003	1.75	0.07(2)	0.88	0.0 (2)
W071-00-000	3.75	0.31(2)	6.43	1.2 (2)
W072-Cr-005	0.06	0.01(2)	1.75	0.04(2)
W073-Cr/Mn/Ni/Ti/V-001	-	-	0.09	0.02(2)
W074-Cr/Mn/Ni/Ti/V-002	0.10	0.01(2)	1.68	0.28(2)
W075-Ti/V-002	0.06	0.01(2)	0.10	0.04(2)
W076-Poly-002	0.48	0.00(2)	2.51	0.37(2)
W077-Mo-001	0.36	0.13(2)	0.31	0.00(2)

Note 1. Sample size shown in parenthesis

Note 2. Insufficient electrical signal for measurement

Note 3. Lifetime measurements subject to large errors due to extreme shallow trap density.

* Measured by LED excitation source

RECOMBINATION LIFETIME MEASURED BY PHOTOCONDUCTIVE-DECAY METHOD
(Q-Switched Nd:YAG Laser Excitation)

Ingot Identification	Lifetime(As-Grown)		Lifetime(Diffused)	
	$\tau(\mu\text{sec})$	σ (Note 1)	$\tau(\mu\text{sec})$	σ (Note 1)
W078-00-000	>14.62	- (2)	--	--
W079-N100-000	121	- (1)	--	--
W080-Ph-001	4.39	0.41 (2)	2.48	0.10 (2)
W081-N/Ni-001	-	-	10.36	1.63 (2)
W082-N/V-001	-	-	0.25	0.01 (2)
W083-N/Fe-001	-	-	--	--
W084-N/Al-001	-	-	--	--
W085-N/Zr-001	-	-	--	--
W086-C-001	3.06	0.52 (2)	2.30	0.05 (2)
W087-Ca-001	2.81	0.63 (2)	2.08	0.54 (2)
W088-Cr-001	Note 2	-	2.23	0.92 (2)
W089-Cu-001	-	-	3.06	0.02 (2)
W090-Mn-001	-	-	2.08	-- (1)
W091-Cr/Mn-002	-	-	0.20	0.09 (2)
W092-Ph-002	-	-	--	--

Note 1. Sample size shown in parenthesis

Note 2. Insufficient electrical signal for measurement

Note 3. Lifetime measurements subject to large errors due to extreme shallow trap density.

* Measured by LED excitation source.

It is also important to recognize that the operating point of solar cells lies above 0.5 volts and therefore a slight shift in the bulk current-segment on the logarithmic I-V plots can change the cell efficiency considerably. On the other hand, junction excess current will have to shift quite a lot on the logarithmic I-V plots to affect the operating point slightly. Figure 9, from our previous work, shows that increased titanium concentration, above $3 \times 10^{11} \text{ cm}^{-3}$, systematically degrades solar cell performance. It is evident from Fig. 10 that primary cause of Ti-induced cell degradation is a decrease in bulk life time. Ti does not appreciably affect the junction excess current. Most impurities, such as Mn, Cr and V etc., behave in a fashion similar to Ti. Some exceptions like Cu and Fe are discussed below.

- Figure 11 shows the transformed I-V curves of Cu-doped cells. Cu starts to degrade the cell performance somewhat above a concentration of $\sim 10^{16} / \text{cm}^3$ (Fig. 9). Fig. 11 shows that unlike Ti, Cu-induced cell degradation can be largely attributed to an increase in junction excess current. We have observed precipitates in heavily Cu-doped ingots and their presence in the high field depletion region can result in excess currents³. It is important to recognize that the increase in junction excess current will depend on quantity and location of the precipitates in the depletion region which may vary considerably from sample to sample even in the same run. As a consequence much larger scatter is observed in the junction excess current of Cu-doped cells. Fig. 11 also demonstrates that Cu at most has very little effect on bulk lifetime. This implies that if trapping centers are present in the silicon, they are either very few in number or have a very small capture cross section.

Figure 12 shows the transformed I-V curves of Fe-doped cells. Iron degrades cell performance both by lowering the bulk life time and by increasing the junction excess current. Again, a much larger scatter is observed in the junction excess current of Fe-doped cells and only the average behavior is indicated by Fig. 12. Our first order mathematical model assumes that impurities degrade the cell performance solely by lowering the lifetime in the base region of the device.^{1,3}

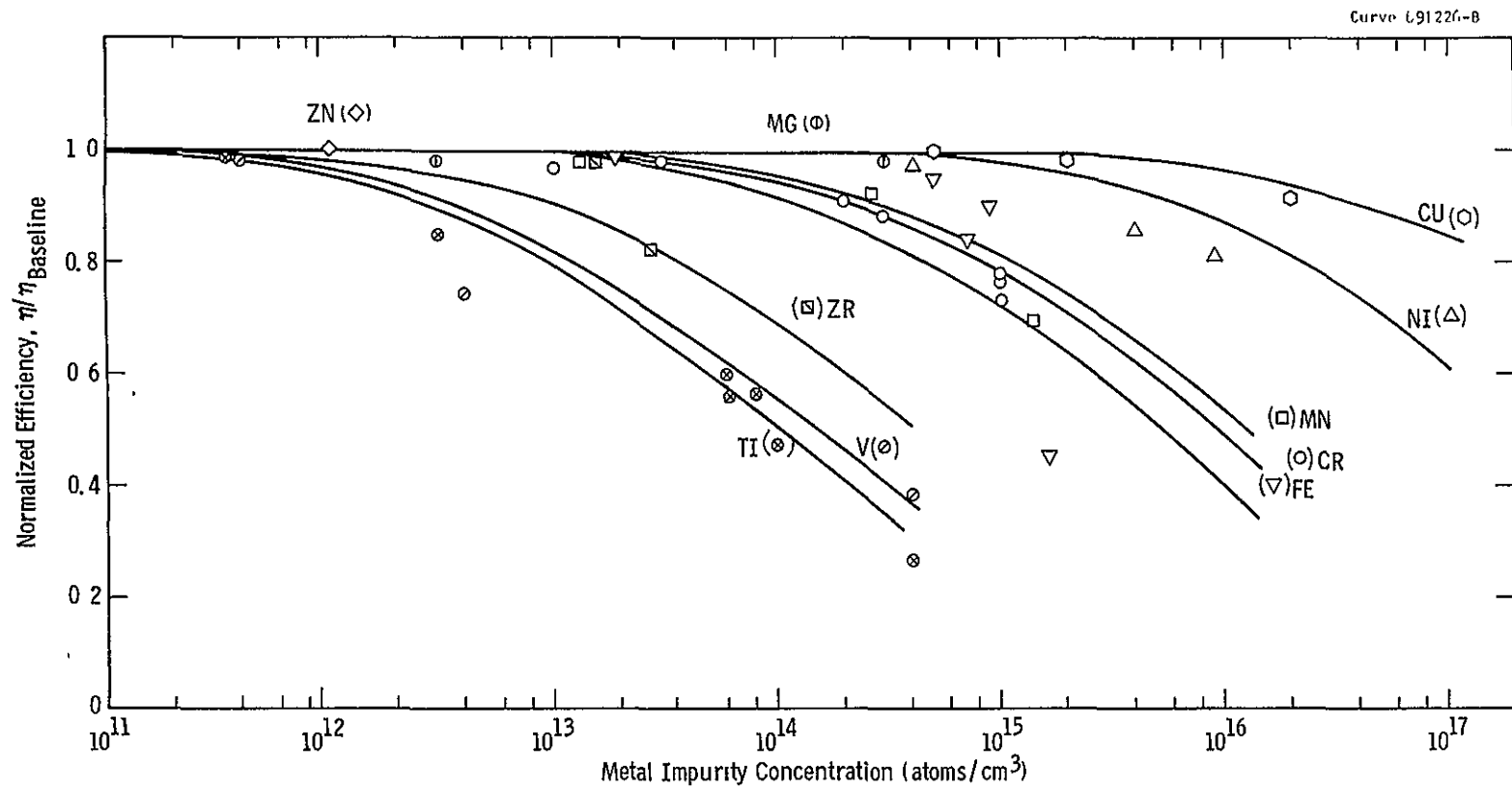


Fig. 9 Normalized solar cell efficiency as a function of substrate metal impurity concentration. Experimental data and model derived curves.

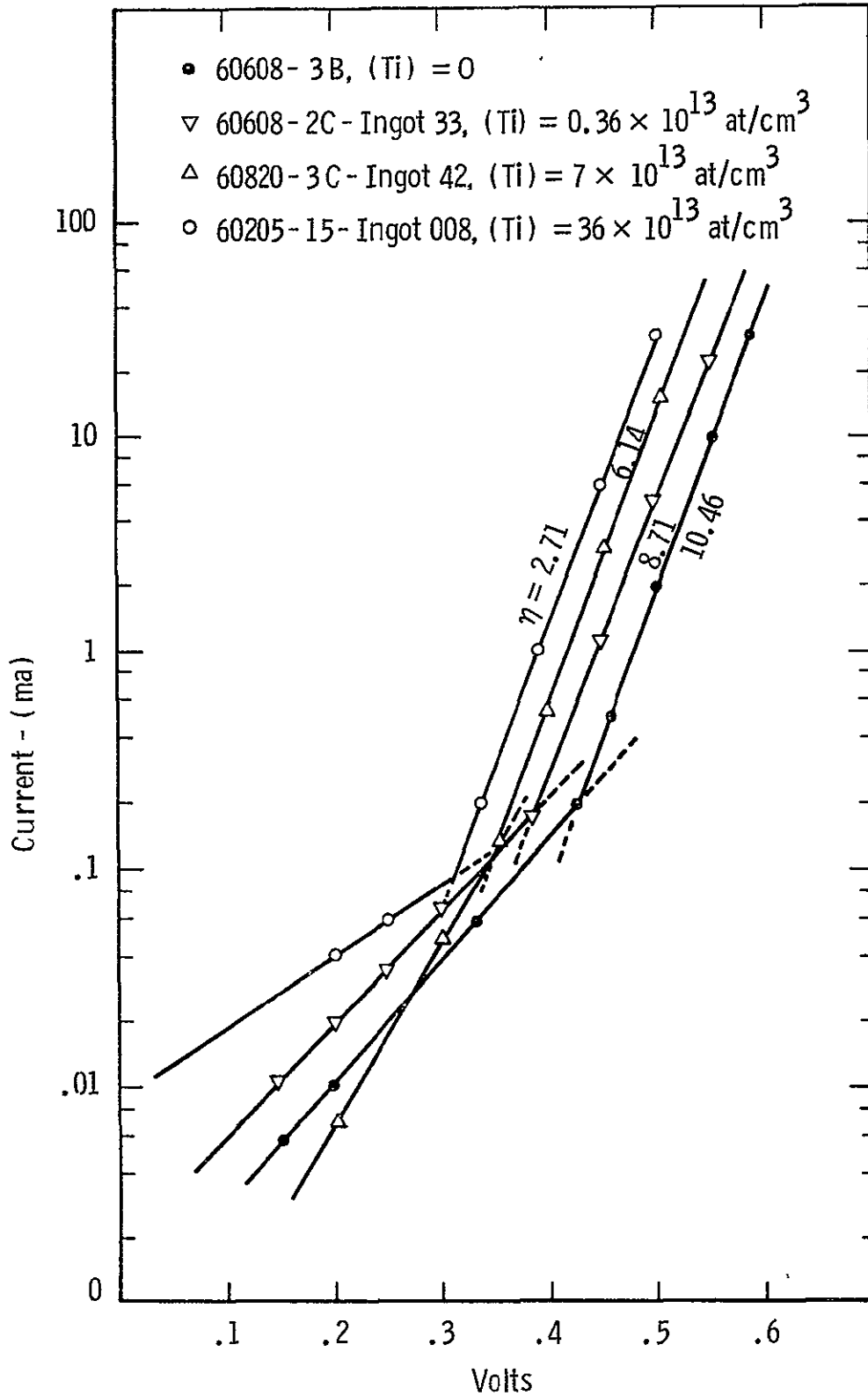


Figure 10 - Transformed dark I-V curves for Ti-doped 4 Ωcm silicon solar cells

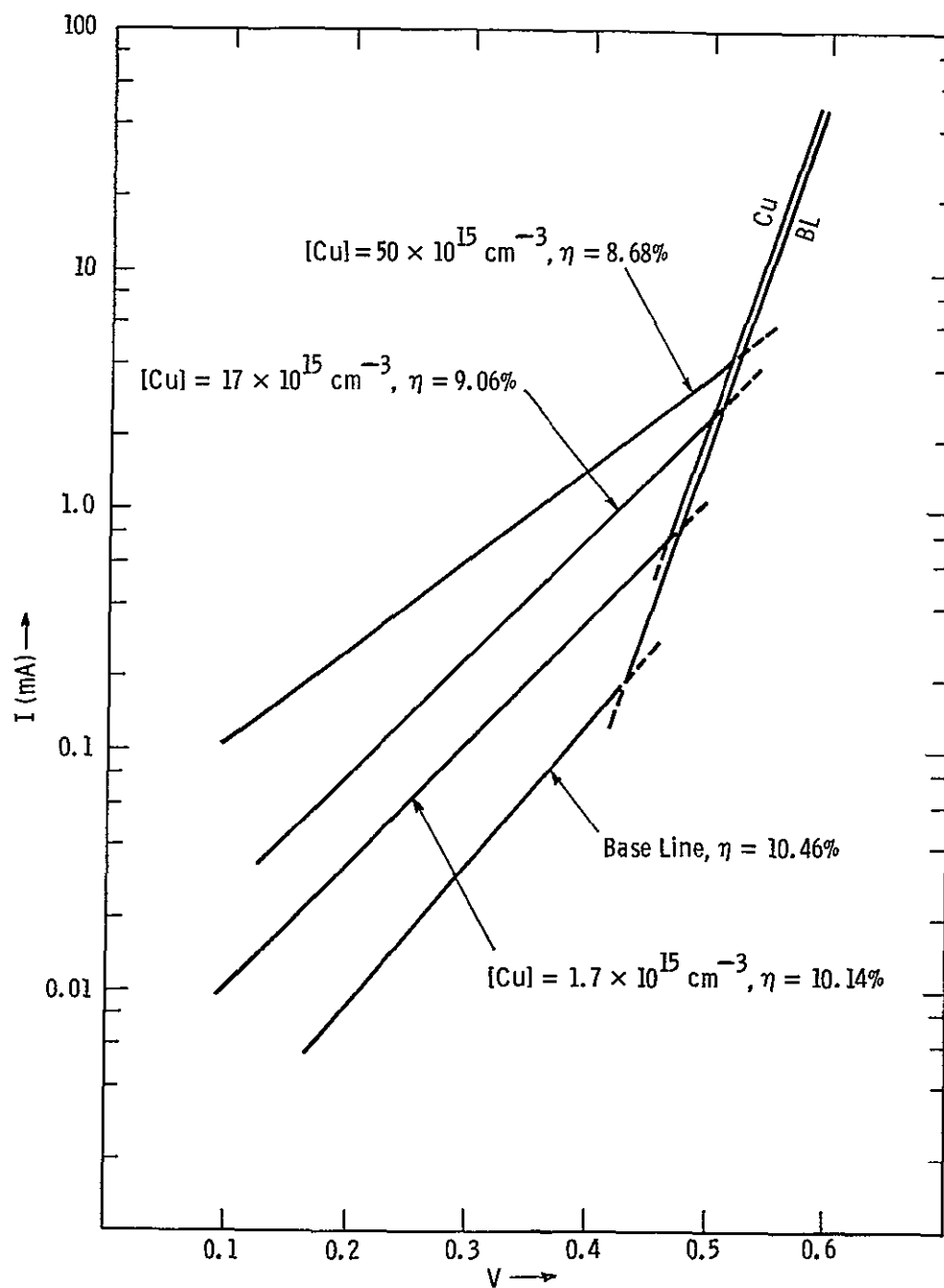


Figure 11 - Transformed dark I-V curves for Cu-doped 4 Ω cm silicon solar cells

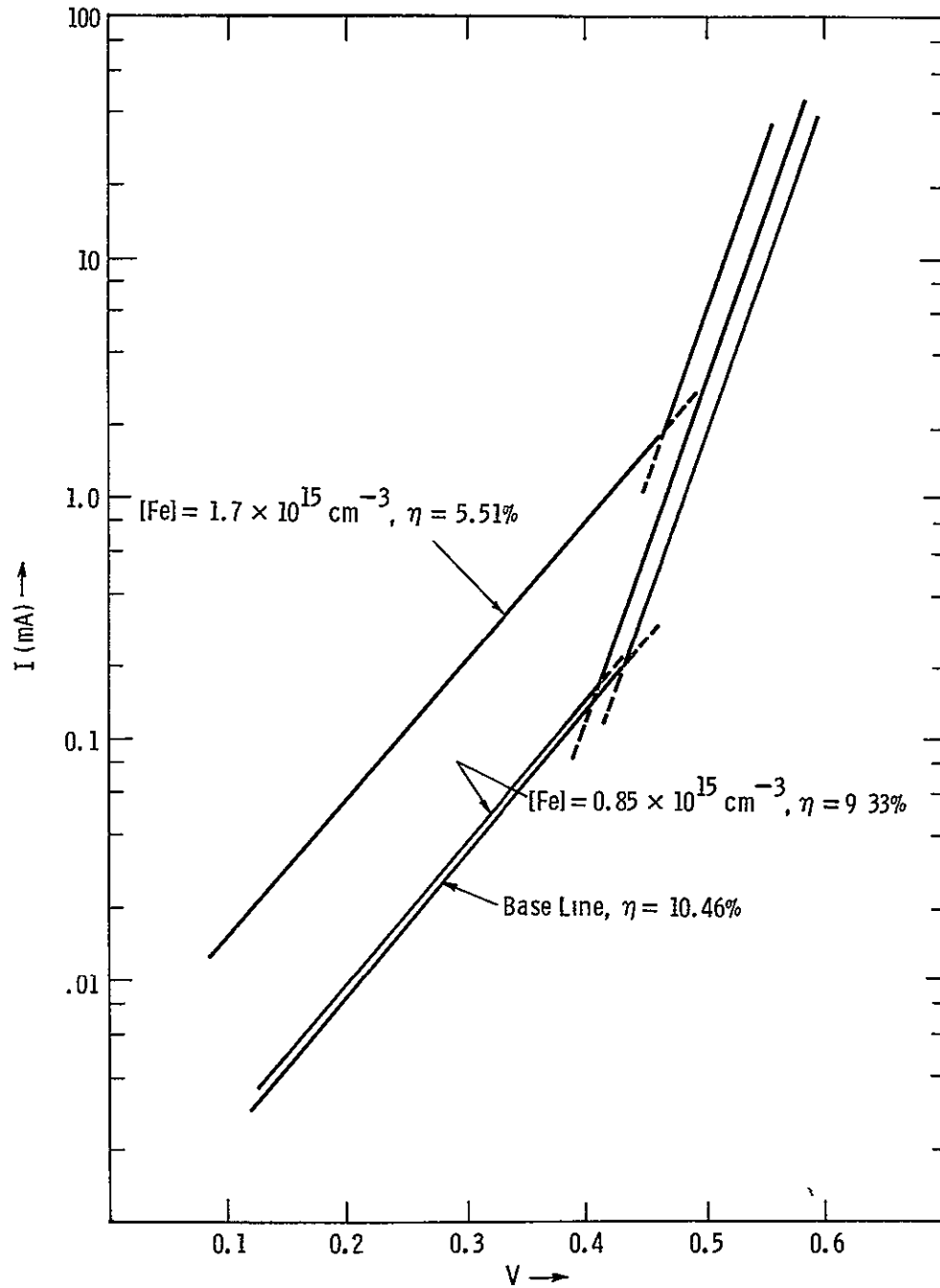


Figure 12 - Transformed dark I-V curves for Fe-doped 4 Ω cm silicon solar cells

The model does not account for the cell degradation by the junction excess current or any other mechanism. Therefore, as expected, an impurity which behaves like iron shows much more rapid degradation than predicted by the model. In fact, Fe-doped cells which have low junction excess current do show very good agreement with the efficiency predicted by the model.

3.4.2.2 Multiply-doped Solar Cells

Assuming multiple impurities do not interact, the calculated performance of cells containing a variety of impurities agrees fairly well with the experimental data^{1,3}. Figure 13 shows transformed I-V curves for Mn and Cu/Mn-doped cells. It is clear that Mn degrades the cell performance only by lowering the bulk lifetime. As noted earlier, Cu primarily increases the junction excess current to degrade the cell performance. Fig. 13 shows that the cell containing Cu and Mn has a bulk lifetime determined primarily by the Mn content, but a junction excess current governed by Cu. Thus Cu and Mn do not show any interaction. In general, Mn data show that multiple impurities do not interact. One striking exception to this behavior are Cu/Ti-doped cells where Cu instead of hurting the cell efficiency actually mitigates the damaging effect of Ti.

3.4.2.3 Comparison of n and p-base devices

Data so far for n-base devices suggest that impurities often show different effects than in the p-base devices, although the basic cell degradation mechanism is lifetime reduction in each case. Titanium and vanadium are significantly less harmful to n-base devices while iron behaves about the same in n or p-base devices. Fig. 14 shows the transformed I-V curves of Ti-doped n and p-base devices. It is quite clear that Ti degrades the electron lifetime much more than hole lifetime which implies that the product of electron trap concentration and trap cross-section is much higher than for the holes. Deep level analysis is required to determine the trap concentrations and cross-sections.

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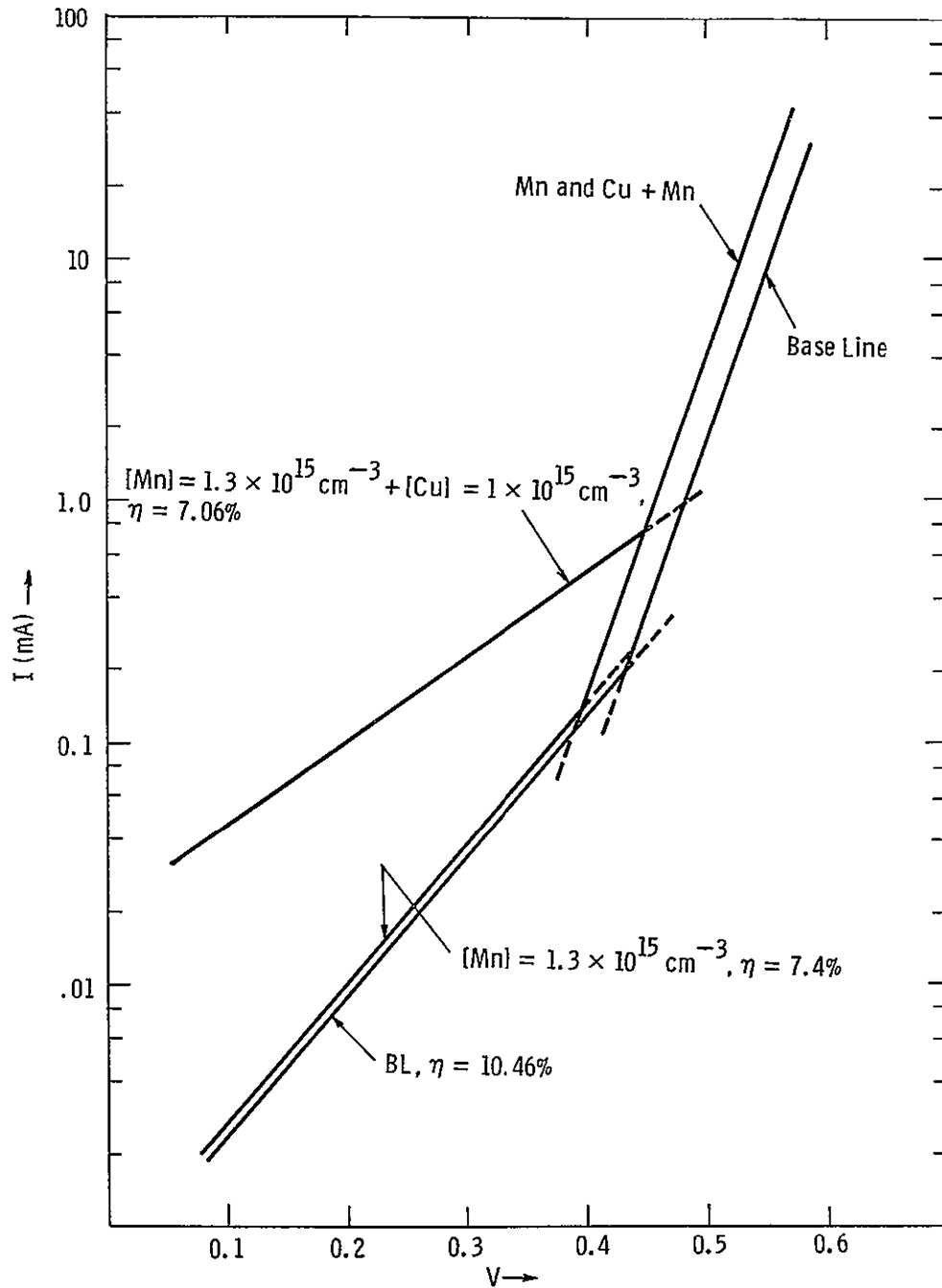


Figure 13 - Transformed dark I-V curves for Mn/Cu-doped 4 Ω cm silicon solar cells

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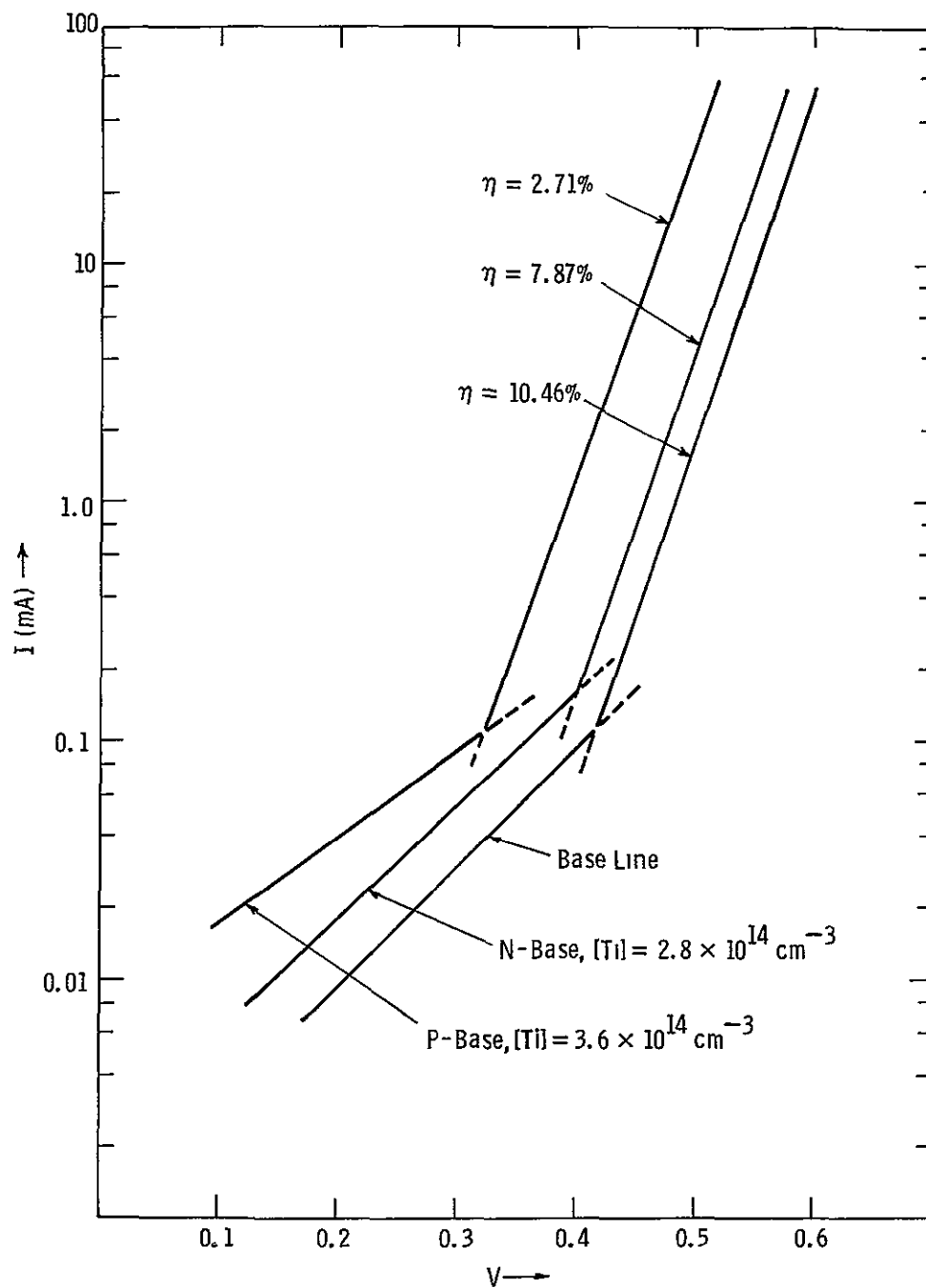


Figure 14 - Transformed dark I-V curves for Ti-doped n and p base 4 Ω cm silicon solar cells

3.4.3 Direct Measurement of Deep Trapping Levels

Metal impurities in silicon material form deep trapping levels which lower the minority carrier lifetime and therefore reduce solar cell efficiency. The magnitude of these effects depends upon the density of traps, their energy level within the silicon band gap, and their characteristic carrier capture properties.

The determination of these properties can be accomplished, in principle, by known techniques which detect the relatively slow emission of trapped carriers at low temperatures. The measurements require the formation of a space charge region provided by a reverse-biased p-n junction, by a Schottky diode, or by an MOS capacitor biased to cause carrier depletion. (Perhaps the most versatile and sensitive of these techniques is "deep level transient spectroscopy" (DLTS) using a reverse biased p-n junction).

In practice it has been found that the density of traps and, in some cases, their physical characteristics are strongly dependent upon the processing history of the material. Thus, to evaluate the effects of impurities in the context of a solar cell, it is desirable to measure material which has been processed in a manner analogous to the typical solar cell fabrication sequence. However, the p-n junction formed in a solar cell is so shallow and abrupt that its diode characteristics are unsuitable for most deep level measurements. Measurements made with Schottky barriers or with MOS capacitors can be made without significantly altering the trap characteristics since no high temperature processing is necessary but these techniques are not as versatile as the p-n junction method.

We have attempted the detection of the deep level traps by thermally stimulated capacitance (TSCAP) measurements on both diffused solar cell p-n junctions and MOS capacitors. The TSCAP apparatus available here has proved incapable of resolving the discrete trapping levels which exist within impurity-doped solar cell material.

Tests on our samples with similar apparatus at the National Bureau of Standards in Gaithersburg, MD provided identical results. So far neither we nor personnel at Bureau of Standards have determined the basis for the apparent lack of sensitivity of the method.

However, in a parallel series of experiments we have obtained data on this same material by DLTS measurements of Schottky diodes or solar cell diffused p-n junctions. In these experiments, which are as yet preliminary, some of the characteristics of the deep level traps have been identified and are compiled in Tables 8, 9 and 10.

The reason for the disagreement in data among the various investigators is not completely clear. It does not seem likely that processing variations have caused changes in trap levels although it is possible. Extensive studies at the Bureau of Standards, on other samples, have shown that large non-uniformities in trap densities can exist even in single silicon wafers.

The projected usefulness of further characterization of deep level traps is very high. Fundamental data on trap density and carrier capture rates are directly applicable to cell performance modelling and will become ever more valuable as materials with multiple impurities are considered for use. In particular, the process-dependent nature of deep level traps must be considered, both to predict what processes can be used, and perhaps to develop processes which are capable of de-activating existing impurities. In this regard, it is essential that there be a close coordination between the processing studies and trapping measurements.

In evaluating the usefulness of trap measurement techniques, it is interesting to note that the DLTS apparatus designed and used by investigator C has been able to employ solar cell type diffused junctions directly. This capability is extremely significant in that it allows a full spectrum of measurements to be made upon realistic solar cell material.

Table 8
Material: W008 Ti 001 (Titanium)

Investigator	Device/ Material	Electron Trap		Hole Trap	
		Level (eV)	Density (cm ⁻³)	Level (eV)	Density (cm ⁻³)
C	p-n junction	E _c -0.264	2.59 x 10 ¹³	E _v +0.29	1.45 x 10 ¹³
C	n-type material	E _c -0.256	--		
C	Schottky barrier			E _v +0.27	--
B	Schottky barrier			E _v +0.2	3.5 x 10 ¹³
A	Schottky barrier	E _c -0.182	>7 x 10 ¹²	E _v +0.470	8 x 10 ¹²
		E _c -0.336	>15 x 10 ¹²		

Table 9

Material: p-type silicon, vanadium doped

Investigator	Device/ Material	Electron Trap		Hole Trap	
		Level (eV)	Density (cm ⁻³)	Level (eV)	Density (cm ⁻³)
A	Schottky barrier/ W035V002	$E_c - 0.746$	$>10^{14}$	$E_v + 0.072$	$\approx 10^{14}$
C	Schottky barrier/ W009V001			$E_v + .42$	

Table 10

Material: p-type silicon, variously doped

Investigator B

Dopant	Device/Material	Level	Density (cm ⁻³)
Nickel	Schottky barrier/	"shallow" hole trap	2×10^{13}
Chromium	Schottky barrier/	Ev+0.19	1×10^{14}

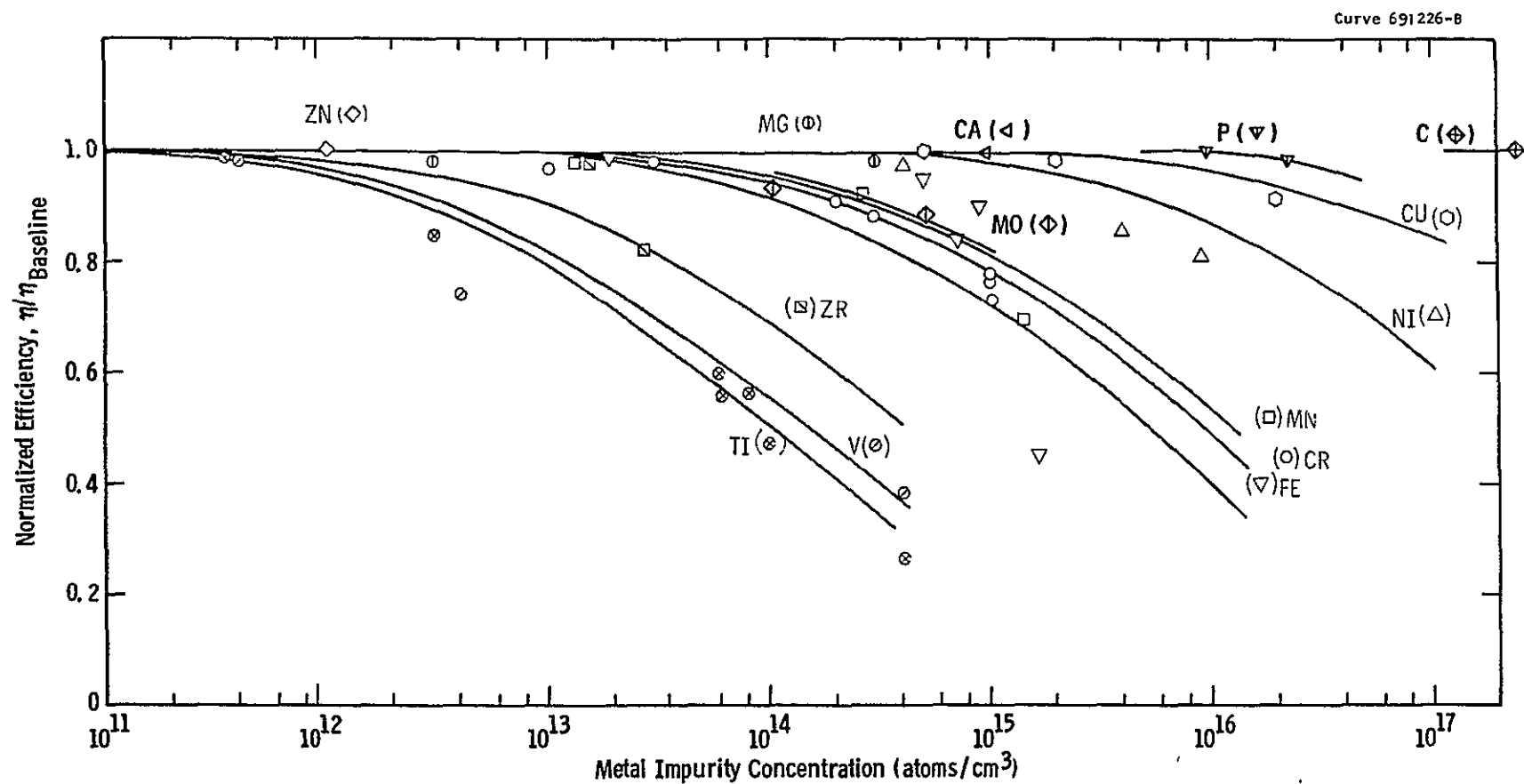


Figure 15 – Normalized solar cell efficiency as a function of substrate metal impurity concentration. Experimental data and model derived curves

We plan to further evaluate this type of apparatus to determine whether it is an effective tool for deep level studies.

3.4.4 Model Analysis of Recent Impurity Data

Some recently obtained data for 4 ohm-cm p-base devices are shown in Fig. 15 along with the model projection of the impurity degradation behavior expected for each species. (I-V data appear in Appendix 7.3). The observed behavior of molybdenum is similar to manganese and chromium and results in significant cell degradation at concentrations above 10^{14} cm^{-3} . I-V measurements confirm that the observed degradation is dominantly associated with base-region lifetime loss and therefore should be adequately represented by the model predictions.

The results shown for calcium at 10^{15} cm^{-3} indicate that it should not cause significant cell degradation at this level and higher concentrations probably cannot be reached in single crystal material.

The behavior of phosphorus is of particular interest since it is a major impurity in the silicon source materials and is costly as well as difficult to remove. The data shown indicate that cell performance is unaffected below 10^{16} cm^{-3} and degraded only about 1% at $3 \times 10^{16} \text{ cm}^{-3}$. It should be noted that phosphorus is a distinctly different sort of impurity than most of those previously studied. Phosphorus acts as shallow donor center in silicon and in general has slight effect on minority carrier lifetime. It is necessary therefore, in the presence of high phosphorus concentrations, to "compensate" the silicon to the resistivity required for the solar cell. This is accomplished, in the case of p-type crystal, by increasing the p-type dopant (boron) so that the difference between the boron and phosphorus levels is the same as the boron concentration would have been with no phosphorus present. It is obvious this becomes increasingly difficult as the phosphorus level increases. A 4 ohm-cm p-type crystal requires a net concentrations of acceptors (boron) of $3 \times 10^{15} \text{ cm}^{-3}$ so that if the donor level (phosphorus) is, say $3 \times 10^{16} \text{ cm}^{-3}$ then the crystal must be grown with boron concentration accurately fixed at $3.3 \times 10^{16} \text{ cm}^{-3}$.

The cell degradation associated with phosphorus is the result of the loss of carrier mobility due to carrier scattering by the ionized phosphorus and boron atoms. In the example given above, the mobility is reduced about 24% based on Irwin's Curves⁸ and the diffusion length about 13%, a reduction which is insufficient to produce significant cell degradation in non-backfield cells of the type we have used to examine impurity effects. The cell performance in compensated material can be predicted using the existant model formulation despite the difference in the mechanism of degradation.

The model analysis is fundamentally based on the minority carrier diffusion length in the silicon and its dependence on the concentration of impurities. The diffusion length depends on the lifetime, γ :

$$L = \sqrt{D\gamma} \quad \text{Eq. 3.4 (1)}$$

and diffusion constant, D , which can be expressed in terms of the mobility, $D = \mu V_T$

$$L = \sqrt{\mu V_T \gamma} \quad \text{Eq. 3.5}$$

where $V_T = kT/q$, the thermal voltage, .026 volts at 300°K. The model derivation assumes that mobility is constant and that lifetime varies with the impurity concentration, N_x as:

$$\begin{aligned} 1/\gamma &= 1/\gamma_x + 1/\gamma_o \\ 1/\gamma &= C_{Tx} N_x + 1/T_o \end{aligned} \quad \text{Eqs. 3.6}$$

where

γ_o is the baseline lifetime and

γ_x is the impurity dependent component of lifetime

C_{Tx} is a constant

An analogous situation would prevail if we were to assume that lifetime remains constant and ionized impurity scattering causes mobility to vary.

Mobility is then expressed as:

$$1/\mu = 1/\mu_I + 1/\mu_L$$

or as a function of the concentration of ionized centers, N_y as:

$$1/\mu = C_{\mu x} N_y + 1/\mu_L \quad \text{Eq. 3.7}$$

where μ_I is the mobility due to impurity scattering,

μ_L is the intrinsic mobility associated with lattice scattering and

$C_{\mu x}$ is a constant.

Examination of equation 3.5 shows that the diffusion length and therefore the cell performance is equally effected by a proportional change in either γ or μ provided the other remains constant. Therefore, the complete symmetry of Eqs. 3.6 and 3.7 assures that the relationships between cell performance and impurity concentration used in the model are functionally identical for mobility or lifetime degradation provided only one of the two mechanisms is active. An independent measurement of lifetime or mobility is necessary to distinguish between them. In our work, the measurement of OCD lifetime provides this information and permits proper interpretation of the constants derived from the data fit. These constants, of course, have different meanings in the two cases. Aluminum, like phosphorus, is also a shallow center, and although an acceptor might be expected to follow the same general behavior, there is evidence that aluminum acts both as scattering center and as a recombination center. This significantly alters the model equations so that the diffusion length is functionally related to the number of aluminum atoms as

$$L = (AN_x^2 + BN_x + C)^{1/2} \quad \text{Eq. 3.8}$$

where A, B and C are constants.

This implies a more rapid degradation with increasing concentration than would obtain with only one active mechanism.

The experimental data at 3×10^{16} indicates a greater cell degradation than can be explained by mobility loss alone but additional data are necessary to determine if the rate behavior follows Eq. 3.8.

Data are also shown in Figure 15 for carbon at a concentration of $3 \times 10^{17} \text{ cm}^{-3}$ which resulted in a twinned crystal. The cell performance was degraded about 5% largely due to degradation of the junction. Neither lifetime nor mobility seem to have been significantly affected. It seems very likely that breakdown of crystal growth rather than electrical activity effects will limit the amount of carbon that can be tolerated in the silicon.

4. Conclusions

Silicon dendritic web effectively segregates impurities to the melt during crystal growth. Thus it may be feasible to employ a solar grade silicon as feedstock so long as the impurity concentration is kept below about 10^{18} to 10^{19} cm^{-3} . The segregation coefficients of typical metals during web growth are estimated from theory and experiment to be about 2.5 times that for Czochralski pulling. Solar cells fabricated on web growth from melts containing Mn, Cr, Fe, and Ni showed no efficiency reduction compared to cells made on uncontaminated silicon; Ti and V reduce efficiency to about 75% of these baseline devices.

The generation of recombination centers during heat treatment of uncontaminated silicon appears to be thermally-activated (over the range 500 to 1000°C). The process can be characterized by an "activation" energy of 1.5eV.

No synergic behavior is evident between boron or the metals Mn, Cu, or Cr when they are present in solar cells made on low resistivity (0.2 ohm-cm) silicon. The cell efficiencies on the low resistivity material are comparable to those of devices made on 4 ohm-cm material.

Quantitative I-V analyses indicate that Fe in high concentration degrades both minority carrier lifetime and causes excessive leakage currents in solar cells. Thus, the deviations of the behavior of iron-doped ingots from our Model calculations can be explained. Cu and Mn show no synergism when present in the silicon from which solar cells are made. Mn degrades lifetime and Cu effects junction excess currents.

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5. Program Status

5.1 Present Status

The Program is on schedule in all elements, Figure 16, except ingot chemical analysis which lags the schedule by one month. During this quarter we have:

- . Grown fourteen ingots (12 Czochralski and two float zone). This completes all of the ingot requirements for Tasks 1, 2 and 5 of the program.
- . Completed carbon and oxygen analysis for selected ingots. Data indicates no deviation from previous results in our growth apparatus.
- . Calibrated laser-excited PCD apparatus for n-base silicon. Completed lifetime measurements for samples from ingots before and after cell processing.
- . Measured silicon lifetime as a function of furnace quench temperature (precursor to gettering experiments)
- . Demonstrated theoretically and experimentally the small segregation coefficients for metals during silicon web growth
- . Demonstrated by quantitative I-V measurements the very different degradation mechanisms in solar cell performance due to impurities like Ti (which lower lifetime) and Cu (which increases junction leakage)
- . Initiated modeling of impurity effects due to Mo, C, and P in silicon solar cells.

5.2 Future Activity

During the coming quarter we will complete the growth of all second generation impurity-doped n-base ingots and all float zone ingots.

Approximately 32 samples are undergoing irradiation for subsequent neutron activation analysis. This data should be available to supplement the mass spectroscopy data by the end of the next quarter. We have not yet been able to chemically detect Mo or Zr and, depending the activation results, some additional effort to analyze for these impurities may be undertaken. Analysis of n-base ingots by lifetime and solar-cell performance should be complete. Modeling activity will be extended to encompass the n-base data. Detailed I-V analysis and thermally stimulated measurements will be continued to more fully characterize impurity effects in silicon.

6. REFERENCES

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PROPOSED PROGRAM
MILESTONE CHART

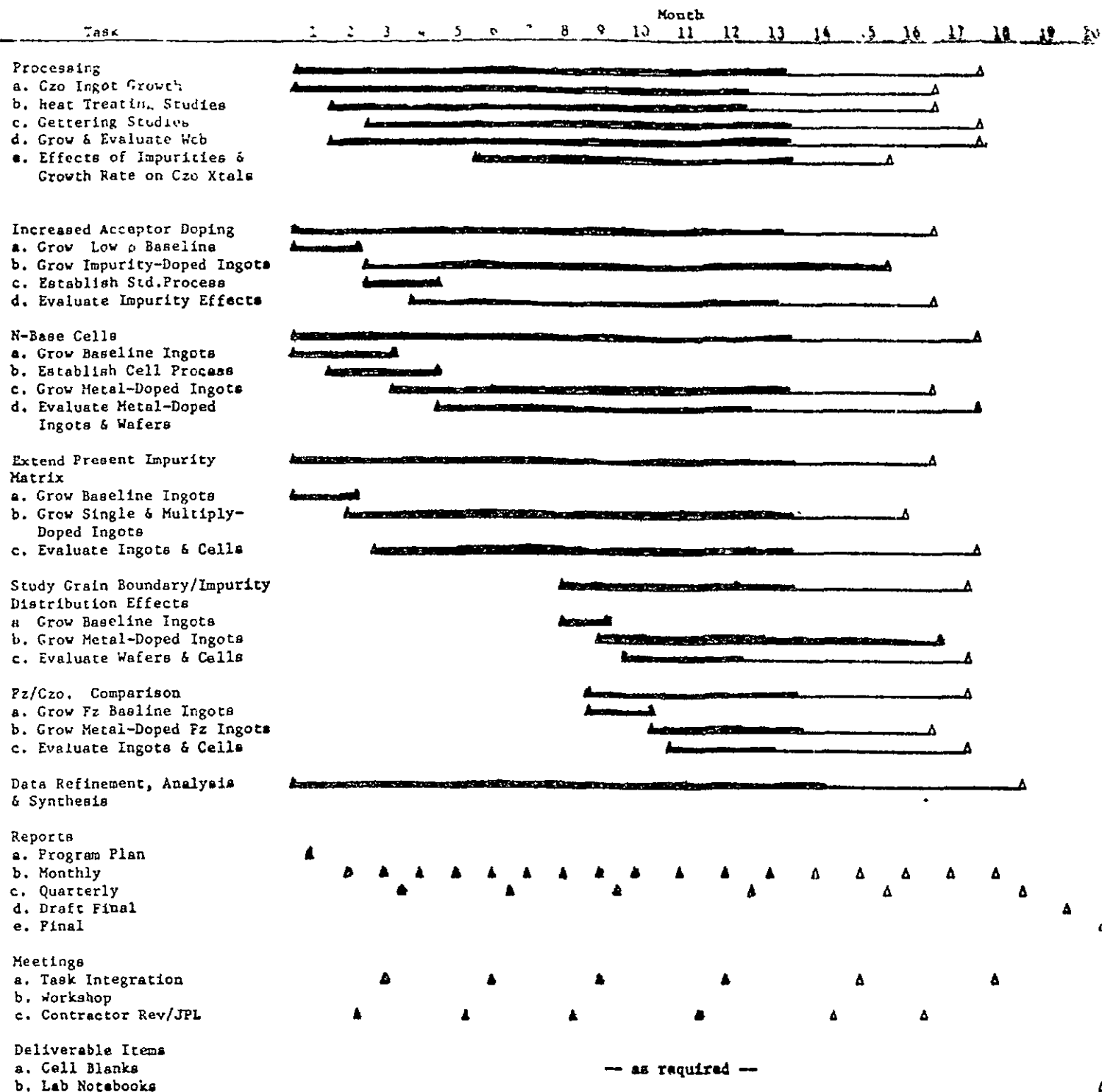


Figure 16 - Proposed Program Milestone Chart

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7.1 Czochralski Ingot Resistivity, Etch Pit Concentration, Metal Impurity Concentration and Segregation Coefficient Data.

Table 7.1 Ingot Resistivity and Etch Pit Density

<u>Ingot Identification</u>	<u>TGT Resistivity (ohm-cm)</u>	<u>Actual Resistivity (ohm-cm)</u>	<u>Etch Pit Density (/cm²)</u>
W-054-00-000	4.0 (B)	4.3 - 3.8	0 - 4.25 K **
W-055-Cu-004	4.0 (B)	4.1 - 3.7	0.5 K - 25 K
W-056-Cu-005	4.0 (B)	4.4 - 3.75	2.5 K - 10 K
W*-057-00-000	0.5 (B)	0.46 - 0.47	0.5 K - 1.25 K
W*-058-00-000	0.2 (B)	0.22 - 0.18	0 - 0.2 K
W*-059-00-000	0.05 (B)	0.05 - 0.053	0 - 2 K
W-060-00-000	1.5 (P)	2.1 - 1.0	0 - 1 K
W-061-Cr/Ti-001	4.0 (B)	5.0 - 4.0	3 K - Clusters
W-062-N/Cu-001	1.5 (P)	2.0 - 0.95	0.4 - 4 K
W-063-N/Cr-001	1.5 (P)	2.2 - 1.7	1 K - 40 K
W-064-N/Mn-001	1.5 (P)	2.2 - 1.35	1 K - 3 K
W-065-N/Ti-001	1.5 (P)	1.9 - 1.7	0 - 2 K
W-066-Ti-005	4.0 (B)	6.0 - 3.9	1 K - 4 K
W-067-Cr/Mn/Ti-001	4.0 (B)	5.5 - 5.2	1 K - 4 K
W-068-Cr-004	4.0 (B)	5.2 - 5.1	1 K - 5 K
W-069-Fe-004	4.0 (B)	5.8 - 5.0	0.4 K - Gross Lineage
W-070-Al-003	4.0 (B)	2.2 - 1.1	0 - 1 K
W-071-00-000	4.0 (B)	4.1 - 3.3	1 K - 4 K
W-072-Cr-005	4.0 (B)	5.0 - 4.5	0 - 2 K
W-073-Cr/Mn/Ni/Ti/V-001	4.0 (B)	5.0 - 3.8	1 K - 40 K
W-074-Cr/Mn/Ni/Ti/V-002	4.0 (B)	4.4	400 - 30 K
W-075-Ti/V-002	4.0 (B)	4.8 - 3.9	0 - 10 K
W-076-Poly-002	4.0 (B)	4.8 - 3.0	N/A (Poly)

Table 7.1 Ingot Resistivity and Etch Pit Density (cont.)

<u>Ingot Identification</u>	<u>TGT Resistivity (ohm-cm)</u>	<u>Actual Resistivity (ohm-cm)</u>	<u>Etch Pit Density (/cm)</u>
W-077-Mo-001	4.0 (B)	4.3 - 3.8	0 - Gross Lineage
W-078-00-000	4.9 (B)	4.3 - 3.3	0 - 80 K
W-079-00-000	1.5 (P)	2.3 - 1.1	1 K - 10 K
W-080-Ph-001	4.0 (B)	6.3 - 3.8	0 - 5 K
W-081-N/Ni-001	1.5 (P)	2.2 - 1.4	1 K - 4 K
W-082-N/V-001	1.5 (P)	1.8 - 1.5	0 - 6 K
W-083-N/Fe-001	1.5 (P)	2.1 - 1.3	1 K - Gross Lineage
W-084-N/Al-001	1.5 (P)	7.5 - 1.9	1 K - 80 K
W-085-N/Zr-001	1.5 (P)	2.4 - 1.5	1 K - 20 K
W-086-C-001	4.0 (B)	4.0 - 3.5	0 K - 20 K ⁺
W-087-Ca-001	4.0 (B)	3.8 - 3.4	0 ⁺⁺
W*-088-Cr-001	0.2 (B)	0.2 - 0.18	1 K - 20 K
W*-089-Cu-001	0.2 (B)	0.21 - 0.19	0 - 20 K
W*-090-Mn-001	0.2 (B)	0.21 - 0.20	1 K - 3 K
W-091-Cr/Mn-002	4.0 (B)	5.5 - 3.5	0 - Gross Lineage
W-092-Ph-002	4.0 (B)	1.7 - 5.6	0 - 1 K
W-093-Mn-004	4.0 (B)	4.9 - 5.3	1 K - 5 K
W-094-Mn-005 (Poly)	4.0 (B)	2.8 - 4.2	N/A
W-095-Mn-006 (F)	4.0 (B)	4.2 - 4.9	0 - 12 K
W-096-Mn-007 (S)	4.0 (B)	4.6 - 4.6	0 - 2 K
W-097-00-000	4.0 (B)	3.2 - 4.2	0
W-098-Mo-002	4.0 (B)	3.6 - 4.3	0 - 10 K
W-099-FZ-001	4.0 (B)	4.2 - 4.4	5 K - 20 K
W-100-Cu/Ti-002	4.0 (B)	3.4 - 5.2	0 - Gross Lineage

Table 7.1 Ingot Resistivity and Etch Pit Density (cont.)

<u>Ingot Identification</u>	<u>TGT Resistivity (ohm-cm)</u>	<u>Actual Resistivity (ohm-cm)</u>	<u>Etch Pit Density (/cm)</u>
W-101-FZ-002	4.0 (B)	4.4 - 4.9	3 K - 20 K
W-102-Ti-006 (Poly)	4.0 (B)	3.8 - 6.4	N/A
W*-103-Ti-001	0.2 (B)	0.23 - 0.25	0 - 30 K
W-104-Cu/Ti-003	4.0 (B)	3.8 - 4.2	2 K - Gross Lineage
W*-105-V-001	0.2 (B)	0.23 - 0.26	3 K - Gross Lineage
W-106-N/Al-002	1.5 (P)	2.1 - 2.9	0

* Use of asterisk indicates low resistivity p-type ingot.

** The first figure is etch pit density of the seed; second figure etch pit density of extreme tang end of ingot. The first value shown is indicative of dislocation density in slices used for cell fabrication.

+ Twinning due to high carbon concentration occurred after approximately three inches of crystal growth.

++ Multiple crystal growth due probably to CaO formation.

Table 7.2 Ingot Impurity Concentration

<u>Ingot Identification</u>	<u>Target Concentration</u> <u>10¹⁵ atoms/cm³</u>	<u>Calc. Concentration</u> <u>10¹⁵ atoms/cm³</u>	<u>Measured Concentration</u> <u>10¹⁵ atoms/cm³</u>
W-054-00-000	N/A	N/A	N/A
W-055-Cu-004	0.1	0.06	<1
W-056-Cu-005	60	90	70
W*-057-00-000	N/A	N/A	N/A
W*-058-00-000	N/A	N/A	N/A
W*-059-00-000	N/A	N/A	N/A
W-060-00-000	N/A	N/A	N/A
W-061-Cr/Ti-001	Cr: 1.1 Ti: 0.02	Cr: 1.0 Ti: 0.017	Cr: 1.0 Ti: <1.0
W-062-N/Cu-001	2.5	2.0	2.0
W-063-N/Cr-001	0.83	0.88	1.0
W-064-N/Mn-001	1.0	0.64	2.0
W-065-N/Ti-001	0.37	0.30	0.75**
W-066-Ti-005	0.06	0.048	<0.2
W-067-Cr/Mn/Ti-001	Cr: 0.44 Mn: 0.50 Ti: 0.006	Cr: 0.3 Mn: 0.36 Ti: 0.0039	Cr: 0.3 Mn: 0.7 Ti: <0.2
W-068-Cr-004	1.0	1.0	1.0
W-069-Fe-004	0.98	0.92	<1.5
W-070-Al-003	50 (4.75)	20 (1.9)	100 (3.0)
W-071-00-000	None	N/A	N/A
W-072-Cr-005	0.4	0.21	0.28
W-073-Cr/Mn/Ni/Ti/V-001	Cr: 0.48 Mn: 0.46 Ni: 2.0 Ti: 0.004 V: 0.004	Cr: 0.34 Mn: 0.31 Ni: 1.3 Ti: 0.005 V: 0.007	Cr: 0.28 Mn: 0.8 Ni: <2.0 Ti: <0.35 V: <0.35

Table 7.2 Ingot Impurity Concentration (cont.)

Ingot Identification	Target Concentration 10^{15} atoms/cm ³	Calc. Concentration 10^{15} atoms/cm ³	Measured Concentration 10^{15} atoms/cm ³
W-074-Cr/Mn/Ni/Ti/V-002	Cr: 0.08 Mn: 0.08 Ni: 0.5 Ti: 0.0006 V: 0.0006	Cr: 0.054 Mn: 0.64 Ni: 0.28 Ti: 0.0025 V: 0.0015	Cr: 0.25 Mn: 0.25 Ni: <2.0 Ti: <0.25 V: <0.25
W-075-Ti/V-002	Ti: 0.1 V: 0.1	Ti: 0.075 V: 0.11	Ti: <0.25 V: <0.25
W-076-Poly-002	None	N/A	N/A
W-077-Mo-001	1.0	0.65	<0.3
W-078-00-000	None	N/A	None
W-079-00-000	None	N/A	None
W-080-Ph-001	0.6	0.7	(0.8)***
W-081-N/Ni-001	2.3	0.65	<2
W-082-N/V-001	0.4	0.475	0.85
W-083-N/Fe-001	1.0	0.86	<1.5
W-084-N/Al-001	50 (4.7)**	22 (2.1)**	40 (<2.5)**
W-085-N/Zr-001	0.007	0.005	(<0.015)
W-086-C-001	300	N/A	200 - 300
W-087-Ca-001	1.0	0.13	?
W*-088-Cr-001	0.5	0.62	3.3
W*-089-Cu-001	2.3	2.13	Incomp.
W*-090-Mn-001	0.7	0.52	2.75
W-091-Cr/Mn-002	Cr: 0.5 Mn: 0.3	0.3 0.3	1.0 2.75

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Table 7.2 Ingot Impurity Concentration (cont.)

<u>Ingot Identification</u>	<u>Target Concentration</u> <u>10^{15} atoms/cm³</u>	<u>Calc. Concentration</u> <u>10^{15} atoms/cm³</u>	<u>Measured Concentration</u> <u>10^{15} atoms/cm³</u>
W-092-Ph-002	28	N/A	(27-30)**
W-093-Mn-004	0.66	0.46	2.75
W-094-Mn-005 (Poly)	0.9	0.63	2.75
W-095-Mn-006 (F)	0.5	0.42	Incomp.
W-096-Mn-007 (S)	0.63	0.55	Incomp.
W-097-00-000	None	N/A	N/A
W-098-Mo-002	0.22	0.1	<0.3
W-099-FZ-001	None	N/A	N/A
W-100-Cu/Ti-002	Cu 1.0 Ti 0.06	1.25 0.07	Incomp.
W-101-FZ-002	None	N/A	N/A
W-102-Ti-006 (Poly)	0.2	0.18	Incomp.
W*-103-Ti-001	0.3	0.25	Incomp.
W-104-Cu/Ti-003	Cu 2.0 Ti 0.25	2.2 0.12	Incomp.
W*-105-V-001	0.4	0.7	Incomp.
W-106-N/Al-002	6.6	Incomp.	(0.7)

** Value in parenthesis based on resistivity measurement.

*** High Ti value possibly due to vacuum leak in M.S.

Table 7.3 Segregation Coefficients

<u>Element</u>	<u>Segregation Coefficient</u>
Al	3×10^{-2} (2.8×10^{-3})
B	0.8
C	0.05
Ca	?
Cu	8.0×10^{-4}
Cr	1.1×10^{-5}
Fe	6.4×10^{-6}
Mg	3.2×10^{-6}
Mn	1.3×10^{-5}
Mo	$\sim 10^{-6}$
Ni	3.2×10^{-5}
Ph	0.35
Ta	$\sim 10^{-7}$
Ti	3.6×10^{-6}
V	4×10^{-6}
Zn	10^{-5}
Zr	$< 1.5 \times 10^{-7}$

7.2 Solute Partitioning during Silicon Dendritic Web Growth

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SOLUTE PARTITIONING DURING SILICON DENDRITIC WEB GROWTH

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Introduction

The dendritic web process, Fig. 1, produces long, thin silicon ribbons suitable for many semiconductor devices including solar cells.⁽¹⁻³⁾ Because dendritic web growth velocities are relatively large, typically several centimeters per minute, it has been tacitly assumed that the effective segregation coefficients will be nearly unity. However, studies of solar cells fabricated on dendritic web grown from melts intentionally doped with transition metals indicated that the rejection of impurities was more complete than had been supposed.⁽⁴⁾ We undertook the investigation reported here to define more clearly the actual solute partitioning behavior during dendritic web growth.

Experimental Procedure

The experimental procedure for determining the segregation of impurities was simply to grow dendritic web crystals from melts having known impurity content. Thin webs bearing trace amounts of metal impurities which first suggested this study are difficult to analyze by conventional activation or mass spectroscopic techniques. For this reason, electrically active acceptors (Al, Ga, and In), having small interface segregation coefficients were used to mimic the behavior of the transition metals. Dendritic web crystals were grown by the usual technique ⁽²⁾ from melts containing aluminum, indium or gallium. Melt undercoolings during growth were 3 to 4°C and pull rates between 0.7 and 1.7 cm/min were used. The resulting crystals were 10 to 15 mm wide and, depending on growth conditions, ranged from about 0.1 to 0.5 mm in thickness.

The solute content of the melt was determined by adding a weighed quantity of dopant to the crucible before melting the charge. The impurity content of the crystals themselves was calculated from either spreading resistance or four probe resistivity measurements.

Results

Spreading resistance data from traverses made at the center and the edges of the web, established that the impurities were very uniformly distributed across the width and through the thickness of the web. For a few samples there was a suggestion that the solute content increased in a thin skin at the ribbon surface, but this could have been an artifact of the spreading resistance measurements on the angle lapped material. No variation in impurity content was found along the length of the web crystals other than that due to melt depletion. The experimental data for each solute, Table 1, has been expressed in terms of the ratio of an effective web segregation coefficient $C_{sol}/C_{liq}=k_{eff}$ to an equilibrium segregation coefficient value for silicon taken from the literature.⁽⁵⁾ The ratio k_{eff}/k_o is close to unity for Al, Ga and In so that each of the solutes is efficiently rejected into the liquid at the growing interface of the web crystal. The scatter in the data apparently represents uncertainties in the measurement techniques.

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ANALYSIS

During the growth of a wide, thin crystal such as a dendritic web, the liquid is pulled up into a ridge-like meniscus, Fig. 1. To analyze solute rejection for this physical situation we approximated the true meniscus shape by the cylindrical wedge shown in Fig. 2. Because the real meniscus surface lies outside of this wedge, the effective half angle, θ , is probably slightly larger than the real contact angle (11° in the case of silicon⁽⁶⁾)

As the web grows, material is constantly removed from the melt so the diffusion problem must also include fluid flow and the general equation governing the problem is

$$D\nabla^2 C - (\vec{v} \cdot \nabla C) = \frac{\partial C}{\partial t} . \quad (1)$$

In the present case, the symmetry of the problem requires that both $\vec{v}$ and ∇C have only radial components. Further, if we only consider the steady state, Eq. 1 becomes the ordinary differential equation

$$\frac{d^2 C}{dr^2} + \frac{1}{r} \left(1 + \frac{v_o r_o}{D} \right) \frac{dC}{dr} = 0 . \quad (2)$$

where we have used the relation

$$v = - \frac{v_o r_o}{r} \quad (3)$$

Equation (2) is readily solved to give the solute concentration as

$$C = - \frac{B_1}{1 + \beta} r^{-\beta} + B_2 \quad (4)$$

where $\beta = \frac{v_o r_o}{D}$.

The constants B_1 and B_2 can be found by requiring conservation of solute at the interface and assuming perfect stirring in the liquid at distances greater than $r = \delta$ (these are essentially the Burton, Prim, and Slichter assumptions.⁽⁷⁾ Mathematically, these conditions can be expressed as

$$r = r_o: \quad -D \frac{dC}{dr} = v_o (1 - k) C_i \quad (5)$$

where C_i is the interface concentration ($r = r_o$) and

$$r = \delta: \quad C(\delta) = C_\infty \quad (6)$$

Using these relations to solve for B_1 and B_2 , the concentration can be written as

$$C(r) = \frac{C_\infty}{1 + \frac{\beta(1-k)}{1+\beta k} \left[\frac{r_o}{\delta} \right]^\beta} \cdot \frac{\beta(1-k)}{1+\beta k} \left\{ \frac{r_o}{r} \right\}^\beta + 1 \quad (7)$$

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Equation (7) admits to considerable simplification when certain approximations are valid. For example, when $k \ll 1$ as is the case for most metallic impurities in silicon, then

$$C(r) \approx \frac{C_{\infty}}{1 + \beta \left[\frac{r_0}{\delta} \right]^{\beta}} \left(1 + \beta \left[\frac{r_0}{r} \right]^{\beta} \right) \quad (8)$$

If, in addition, $\left[\frac{r_0}{\delta} \right]^{\beta} \ll 1$, then Eq. (8) can be simplified to

$$C(r) \approx C_{\infty} \left(1 + \beta \left\{ \frac{r_0}{r} \right\}^{\beta} \right) \quad (9)$$

Since there is some evidence to suggest that $\beta \sim 10$, even $(r/\delta) \sim \frac{1}{2}$ would make this a reasonable approximation.

Equation (9) yields the steady state solute concentration at the growth front, $r = r_o$.

$$C_i = C_\infty (1 + \beta) . \quad (10)$$

Since $C_s = kC_i$ and the effective segregation coefficient is defined by $k_{eff} = C_s/C_\infty$; we have

$$k_{eff} = k (1 + \beta) , \quad (11)$$

which is distinctly different from the limiting value of $k_{eff} = 1$ obtained in a one-dimensional treatment.

Equation (11) can be put in terms of the web thickness by means of the relation $t = 2r_o \sin \theta$ so that we find

$$k_{eff}/k_o = \left\{ 1 + \frac{v_o t}{2D \sin \theta} \right\} . \quad (12)$$

Equation (12) is obviously invalid as θ approaches zero; however, that limit would also invalidate the initial assumption that the true meniscus shape could be modeled as a wedge. For the time being, θ can be taken as somewhat greater than the contact angle.

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Equation (12) can be evaluated for conditions typical of some of the data in Table 1. Generally, the velocity-thickness product in these cases was the order of $1 \times 10^{-3} \text{ cm}^2/\text{sec}$. Kodera⁵ reports a diffusivity of $7 \times 10^{-4} \text{ cm}^2/\text{sec}$ for aluminum in liquid silicon and we choose an effective wedge angle $\theta = 20^\circ$ as representative of the reported contact angle of 11° ⁶. Using these data in Equation (12), k_{eff}/k_o is found to be 3, as compared with the measured value of about 1.5.

The model also predicts that k_{eff}/k_o should vary directly with the product of web thickness and velocity (vt). We searched for such a trend in the data used to compile Table 1 but the relatively narrow range of vt values available for study coupled with the scatter in the data itself precluded the drawing of any firm conclusions.

The simple model for solute partitioning during web growth predicts fairly well the magnitude of the observed impurity segregation. The disparity between the model's prediction and the measured value of k_{eff}/k_o may stem from (1) errors in the reported values of k_o and D or (2) the imperfect matching of the model to the real physical situation. While a definitive answer to this question awaits more precise experiments, it appears that the model may be applied in a semiquantitative fashion to predict the segregation of solutes in silicon for which $k_o \ll 1$.

Summary and Conclusions

We have examined some experimental and theoretical aspects of solute partitioning during silicon dendritic web growth. The effective segregation coefficient for the three acceptor impurities, Al, Ga and In, is approximately the same as the interface segregation coefficients determined from Czochralski growth experiments reported in the literature. A simplified theoretical model for the web process predicts indeed that the effective segregation coefficient should be of the same order as the interface segregation coefficient. The model also predicts that the ratio of the two coefficients k_{eff}/k_0 should depend linearly on the product of the crystal thickness and growth velocity. Within the uncertainty of our data, we could not verify this dependence.

TABLE 1. SUMMARY OF SOLUTE PARTITIONING DATA FOR SILICON WEB EXPERIMENTS

<u>Solute</u>	<u>Number of Web Crystals</u>	<u>Number of Samples</u>	<u>Initial Solute Concentration (atom fraction)</u>	<u>k_{eff}/k_o</u>	<u>k_o (Ref. 5)</u>
Aluminum	3	6	2.47×10^{-5}	1.47 ± 0.65	0.0028
Gallium	4	7	8.06×10^{-6}	0.97 ± 0.45	0.008
Indium	3	9	2.47×10^{-6}	0.93 ± 0.16	0.0004

Dwg. 6256A82

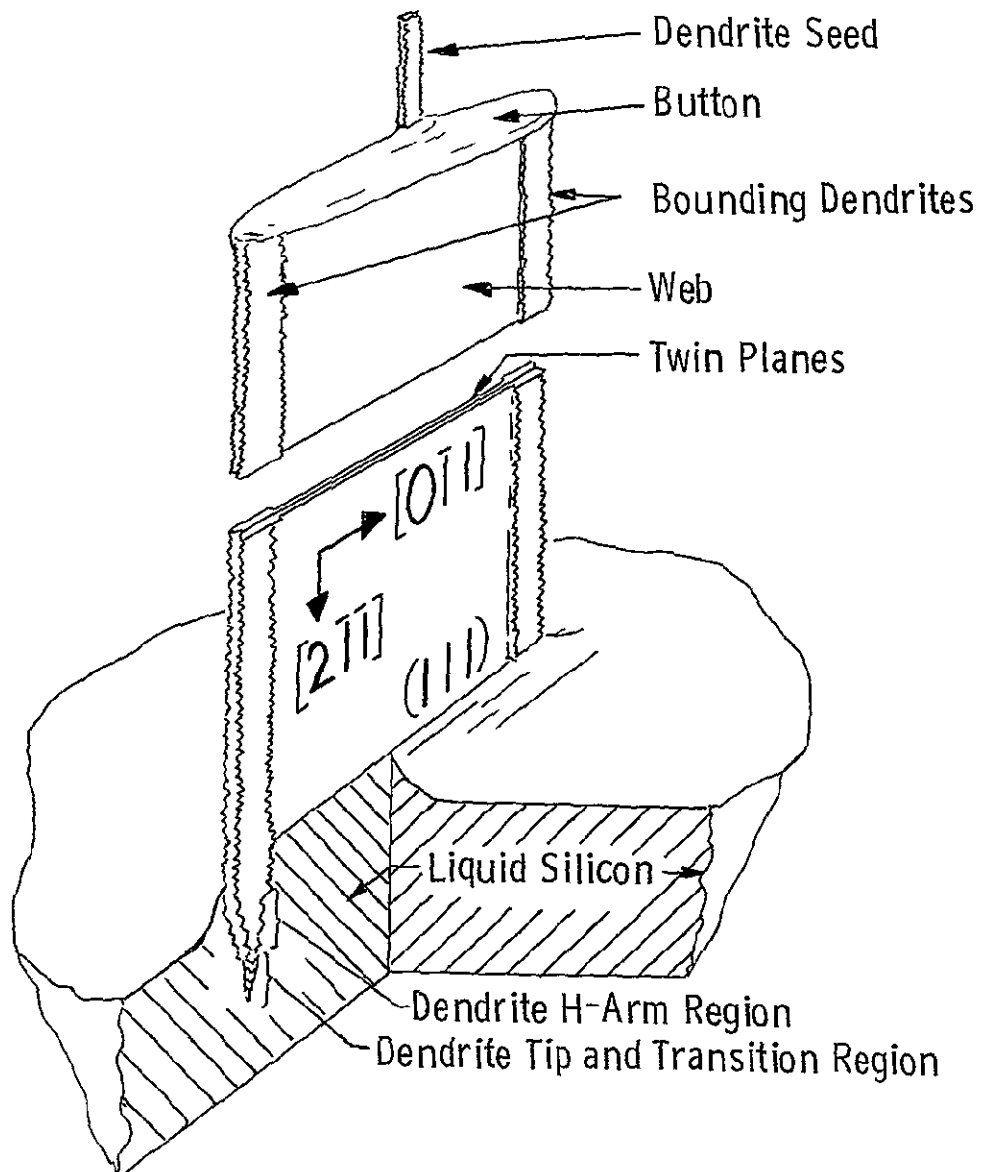


Fig. 1 - Schematic section of Web Growth

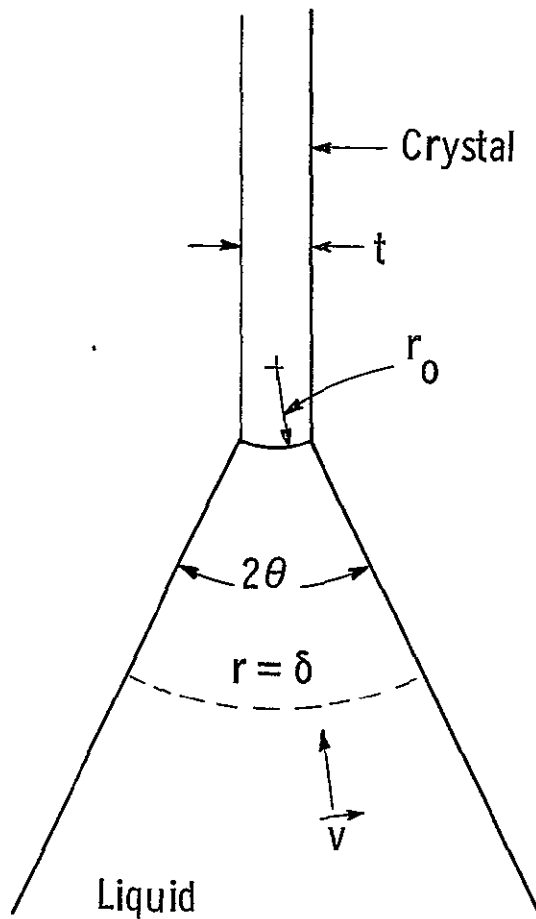


Fig. 2 - Geometry for Diffusion in a Meniscus

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7.3 Photovoltaic Characteristics of Solar Cells Fabricated on Impurity doped Czochralski Ingots

Test conditions: no AR coatings, cell area 1 cm^2 and illumination 91.6 mW/cm^2

Abbreviations: R - calibrated reference device

C - wafers from ingot center

T - wafers from ingot tary and

S - wafers from ingot seed and

B - wafers from uncontaminated baseline ingots

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70829 W083NFE001 (8.6E14) W060 00 000 <70412>
 SOL2 1 /12/78 AM1: P0=91.60MW/CM² NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	FFF	OCD	PCDA	PCDP
1CB	22.70	.567	21.12	-8.705	1.34	.22	.770	10.48	9.10	.00	.00
2CB	22.60	.561	20.99	-8.550	1.36	.17	.769	10.30	9.10	.00	.00
3CB	22.90	.568	21.41	-9.248	1.25	.30	.779	10.71	3.25	.00	.00
4CB	22.90	.565	21.18	-8.093	1.46	-.03	.765	10.47	9.10	.00	.00
5CB	22.80	.568	21.05	-7.944	1.51	-.07	.762	10.44	9.10	.00	.00
1C	19.50	.535	16.97	-5.098	2.64	-1.88	.694	7.66	1.30	.00	.00
2C	20.00	.539	17.53	-5.400	2.43	-1.20	.696	7.93	2.21	.00	.00
3C	19.10	.534	16.74	-5.394	2.43	-1.40	.698	7.53	1.69	.00	.00
4C.*	18.50	.526	15.50	-4.151	3.63	-4.33	.671	6.91	1.56	.00	.00
5C	20.30	.543	18.39	-6.654	1.83	-.70	.740	8.62	2.34	.00	.00
6C	19.40	.534	17.23	-5.890	2.14	-.83	.710	7.77	1.82	.00	.00
7C	19.30	.529	16.99	-5.726	2.20	-.42	.690	7.45	1.69	.00	.00
8C	20.90	.542	17.88	-4.644	3.05	-2.27	.677	8.11	2.34	.00	.00
9C	20.50	.545	18.70	-7.220	1.65	-.11	.742	8.76	3.51	.00	.00
10C	18.80	.530	16.26	-4.833	2.85	-2.86	.699	7.36	1.04	.00	.00
11C	21.00	.544	19.00	-6.915	1.73	.23	.721	8.71	4.55	.00	.00
12C	21.30	.545	18.59	-5.368	2.46	-.69	.682	8.37	3.77	.00	.00
1S	21.40	.550	19.50	-7.204	1.66	.09	.735	9.15	5.85	.00	.00
2S	21.50	.548	19.54	-7.037	1.70	.03	.732	9.12	4.55	.00	.00
5S.*	21.50	.547	17.29	-3.448	5.11	-6.24	.644	8.01	4.55	.00	.00
1T	17.70	.514	15.43	-5.542	2.27	-.25	.673	6.48	1.69	.00	.00
2T	18.30	.521	16.18	-5.824	2.13	-.61	.698	7.04	.91	.00	.00
3T	18.00	.521	16.07	-6.217	1.95	-.37	.709	7.03	1.95	.00	.00
4T	18.40	.525	16.31	-5.888	2.11	-.73	.705	7.20	1.04	.00	.00
5T	18.00	.523	15.94	-5.911	2.10	-.56	.701	6.98	1.69	.00	.00
AVERAGES: 70829 BASELINE W060 00 000 <70412>											
	22.78	.566	21.15	-8.508	1.38	.12	.769	10.48	7.93	.00	.00
STD	.12	.003	.15	.464	.09	.14	.006	.13	2.34	*	*
70829 W083NFE001 (8.6E14)											
	19.63	.535	17.40	-5.932	2.18	-.81	.706	7.85	2.44	.00	.00
STD	1.24	.010	1.26	.772	.39	.81	.020	.77	1.37	*	*
PERCENT OF BASELINE											
	86.2	94.5	82.3	130.3	158	*****	91.8	74.9	30.8	*****	*****
STD%	5.9	2.3	6.5	13.4	41	*****	3.3	8.4	31.5	*****	*****

71104 W084AL001 (2E15) W078 00 000

SOL6 1 /12/78 AM1: PO=91.60MW/CMt2 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDP
1F*	22.50	.558	20.09	-6.064	2.11	-.55	.714	9.49	.00	.00	.00
1B	22.30	.555	19.70	-5.485	2.42	-1.41	.713	9.33	3.90	.00	.00
2B.*	22.50	.551	20.01	-5.753	2.24	-1.14	.719	9.43	3.64	.00	.00
3B	22.70	.553	20.47	-6.369	1.95	-.80	.736	9.77	3.90	.00	.00
4B*	22.20	.546	19.39	-5.126	2.63	-1.73	.701	8.99	2.99	.00	.00
5B.	22.90	.551	20.19	-5.472	2.40	-1.16	.706	9.42	3.90	.00	.00
1C	19.50	.520	16.68	-4.955	2.68	-.81	.656	7.04	.65	.00	.00
2C	20.10	.527	17.70	-5.618	2.25	-.77	.696	7.80	.91	.00	.00
3C	19.80	.525	17.47	-5.674	2.21	-.82	.700	7.69	.78	.00	.00
4C	20.20	.526	17.26	-4.987	2.67	-.44	.649	7.30	.78	.00	.00
5C	20.00	.526	17.54	-5.449	2.34	-1.01	.694	7.72	.78	.00	.00
6C	20.10	.523	17.37	-5.022	2.63	-1.41	.679	7.55	.65	.00	.00
7C	20.20	.525	17.50	-5.226	2.48	-.68	.671	7.53	.78	.00	.00
8C	19.90	.524	17.11	-4.926	2.71	-1.37	.671	7.40	.78	.00	.00
9C	19.70	.526	17.37	-5.863	2.11	-.03	.686	7.52	.78	.00	.00
10C	20.00	.525	17.37	-5.187	2.51	-1.14	.682	7.57	.78	.00	.00
11C	19.70	.525	17.30	-5.565	2.27	-.76	.692	7.57	.65	.00	.00
12C	19.60	.521	16.94	-5.048	2.61	-1.37	.678	7.33	.65	.00	.00
13C	19.60	.520	16.94	-5.061	2.59	-1.26	.676	7.29	.65	.00	.00
1S	20.80	.528	17.97	-5.120	2.57	-.82	.670	7.79	.78	.00	.00
2S	19.80	.523	17.28	-5.381	2.38	-.78	.683	7.48	.78	.00	.00
3S	20.00	.524	17.44	-5.534	2.28	-.04	.670	7.43	.91	.00	.00
4S	20.30	.525	17.59	-5.240	2.47	-.61	.671	7.56	.91	.00	.00
5S	19.90	.526	17.30	-5.306	2.44	-.71	.677	7.49	.78	.00	.00
1T	19.50	.523	16.66	-4.821	2.81	-1.40	.663	7.15	.78	.00	.00
2T	20.00	.529	17.55	-5.499	2.33	-.90	.693	7.76	.91	.00	.00
3T	19.30	.524	17.05	-5.789	2.15	-.59	.698	7.47	.91	.00	.00
4T	19.60	.525	17.21	-5.534	2.29	-.85	.693	7.54	.91	.00	.00
5T	19.70	.527	17.46	-5.889	2.10	-.56	.703	7.71	1.04	.00	.00
6T	20.00	.525	17.44	-5.239	2.48	-1.30	.690	7.66	.91	.00	.00

AVERAGES: 71104 BASELINE W078 00 000

22.70 .553 20.47 -6.369 1.95 -.80 .736 9.77 3.90 .00 .00

STD .00 .000 .00 .000 .00 .00 .00 .000 .00 .00 *

71104 W084AL001 (2E15)

19.89 .525 17.31 -5.331 2.43 -.85 .681 7.51 .80 .00 .00

STD .31 .002 .30 .304 .20 .38 .014 .19 .10 *

PERCENT OF BASELINE

87.6 94.9 84.6 116.3 124 93.2 92.5 76.9 20.6 *****

STD% 1.4 .4 1.4 4.8 10 47.4 1.9 2.0 2.7 *****

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70831 W085N/ZR001 (7E12) W079 00 000
 SOL6 1 /12/78 AM1: PO=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	FFF	OCD	PCDA	PCDB
1R*	22.50	.553	20.18	-6.315	1.98	-.30	.717	9.44	.00	.00	.00
1E.*	21.70	.548	18.35	-4.271	3.51	-3.35	.677	8.52	3.90	.00	.00
2B.*	21.90	.546	19.19	-5.271	2.53	-1.46	.701	8.86	4.55	.00	.00
3B.*	21.50	.521	17.57	-4.089	3.59	-1.58	.612	7.25	1.04	.00	.00
4B.*	22.10	.547	19.08	-4.817	2.89	-2.02	.688	8.80	5.20	.00	.00
5B.*	21.70	.539	18.49	-4.600	3.07	-1.95	.668	8.27	3.38	.00	.00
1C	22.20	.551	19.67	-5.769	2.24	-.70	.705	9.12	5.20	.00	.00
2C	21.60	.548	18.74	-4.862	2.86	-2.42	.701	8.78	4.29	.00	.00
3C	22.20	.552	19.85	-6.132	2.06	-.48	.715	9.27	6.50	.00	.00
4C	21.70	.554	19.44	-6.082	2.09	-1.00	.728	9.26	5.85	.00	.00
5C	21.70	.544	18.47	-4.507	3.20	-2.44	.674	8.42	3.25	.00	.00
6C	21.90	.554	19.22	-5.234	2.59	-1.85	.710	9.11	5.20	.00	.00
7C	21.60	.551	19.32	-6.008	2.12	-1.02	.725	9.13	6.11	.00	.00
8C	21.60	.544	18.38	-4.446	3.27	-2.78	.678	8.42	3.90	.00	.00
9C	21.70	.544	18.86	-5.050	2.68	-1.60	.691	8.62	3.25	.00	.00
10C.*	21.40	.550	18.07	-4.114	3.76	-4.46	.689	8.58	5.46	.00	.00
11C	21.60	.546	18.64	-4.777	2.93	-2.29	.691	8.62	5.20	.00	.00
1S.*	21.80	.538	16.78	-3.036	6.46	-8.04	.610	7.57	2.60	.00	.00
2S.*	22.40	.540	17.64	-3.297	5.45	-5.79	.617	7.89	2.99	.00	.00
3S.*	22.10	.536	16.98	-3.077	6.23	-6.99	.599	7.50	1.95	.00	.00
4S.*	22.00	.531	16.46	-2.898	7.02	-7.99	.579	7.15	1.30	.00	.00
5S.*	22.10	.544	18.47	-4.112	3.70	-3.21	.660	8.39	4.55	.00	.00
1T	22.00	.549	18.85	-4.643	3.07	-2.23	.680	8.69	4.55	.00	.00
2T	22.00	.551	18.96	-4.705	3.02	-2.46	.692	8.87	5.59	.00	.00
3T.*	21.90	.536	17.62	-3.582	4.65	-4.50	.628	7.79	2.60	.00	.00
4T	21.70	.539	18.20	-4.237	3.50	-2.72	.658	8.14	2.60	.00	.00
5T.*	22.10	.533	18.03	-3.847	4.06	-3.12	.629	7.83	2.08	.00	.00
6T	21.80	.533	17.87	-3.963	3.86	-2.67	.628	7.72	1.69	.00	.00

AVERAGES: 70831 BASELINE W079 00 000
 NO BASELINE

	70831 W085N/ZR001 (7E12)										
	21.81	.547	18.89	-5.030	2.82	-1.90	.691	8.73	4.51	.00	.00
STD	.21	.006	.55	.686	.54	.77	.026	.43	1.37	*	*

70926 W086C001 (3E17) W078 00 000
 SOL6 1 /12/78 AM1: P0=91.60MW/CM+2 NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDR
1R*	22.50	.556	20.23	-6.452	1.93	-.15	.718	9.49	.00	.00	.00
1B	21.50	.553	19.82	-7.732	1.52	-.37	.766	9.63	3.51	.00	.00
2F	21.70	.555	20.08	-8.062	1.45	-.25	.771	9.82	4.94	.00	.00
3B	21.50	.553	19.73	-7.399	1.61	-.48	.760	9.55	4.94	.00	.00
4B	21.40	.552	19.61	-7.295	1.64	-.56	.759	9.48	4.16	.00	.00
5B	21.60	.552	19.94	-7.824	1.50	-.37	.768	9.69	4.94	.00	.00
1C	21.50	.549	19.16	-5.768	2.24	-1.44	.727	9.07	3.64	.00	.00
2C	21.50	.551	19.78	-7.527	1.57	-.54	.766	9.59	4.55	.00	.00
3C	21.60	.551	19.63	-6.714	1.82	-.87	.750	9.44	3.90	.00	.00
4C	21.30	.553	19.44	-7.061	1.71	-.53	.750	9.35	4.29	.00	.00
5C	21.60	.552	19.18	-5.569	2.36	-1.79	.727	9.17	3.64	.00	.00
6C	21.00	.546	18.12	-4.690	3.03	-2.93	.700	8.48	2.60	.00	.00
7C	21.40	.549	18.97	-5.544	2.37	-1.74	.724	8.99	3.14	.00	.00
8C	21.50	.550	19.24	-5.865	2.19	-1.63	.737	9.22	3.90	.00	.00
9C	21.80	.551	19.70	-6.413	1.94	-1.03	.744	9.45	3.64	.00	.00
10C	21.70	.551	19.59	-6.328	1.97	-1.13	.743	9.40	3.90	.00	.00
11C	21.60	.549	19.08	-5.468	2.41	-1.61	.716	8.98	3.25	.00	.00
1S	21.50	.547	18.76	-4.998	2.74	-2.38	.709	8.82	2.99	.00	.00
2S	21.50	.551	19.44	-6.415	1.94	-1.13	.746	9.35	4.29	.00	.00
3S	21.40	.543	18.76	-5.242	2.54	-1.74	.706	8.68	2.60	.00	.00
4S	21.30	.549	19.43	-6.922	1.75	-.88	.757	9.36	3.64	.00	.00
5S	21.60	.550	19.77	-7.214	1.66	-.54	.756	9.50	4.16	.00	.00
1T	21.50	.544	18.55	-4.805	2.90	-2.12	.688	8.51	2.34	.00	.00
2T	21.50	.550	19.19	-5.813	2.22	-1.47	.730	9.13	3.64	.00	.00
3T	21.80	.548	19.24	-5.418	2.44	-1.65	.715	9.04	3.12	.00	.00
4T	21.50	.548	19.54	-6.748	1.80	-.79	.748	9.32	3.38	.00	.00
5T	21.90	.548	19.71	-6.138	2.04	-1.35	.743	9.42	3.38	.00	.00
6T	21.90	.548	19.65	-6.002	2.11	-1.40	.738	9.37	3.90	.00	.00

AVERAGES: 70926 BASELINE W078 00 000

	21.54	.553	19.84	-7.662	1.54	-.40	.765	9.63	4.50	.00	.00
STD	.10	.001	.16	.281	.07	.11	.005	.11	.58	*	*
	70926 W086C001 POLY (3E17)										
	21.54	.549	19.27	-6.030	2.17	-1.39	.733	9.16	3.54	.00	.00
STD	.20	.002	.42	.773	.39	.60	.020	.31	.57	*	*
PERCENT OF BASELINE											
	100.0	99.3	97.1	121.3	141	*****	95.8	95.1	78.7	*****	*****
STD%	1.4	.6	2.9	13.3	33	277.7	3.2	4.4	24.4	*****	*****

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70930 W087CA001 (1E15) W078 00 000
 SOL6 1 /12/78 AM1: P0=91.60MW/CM² NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDR
1R*	22.50	.557	20.17	-6.303	2.00	-.27	.716	9.48	.00	.00	.00
1B	22.50	.553	20.21	-6.094	2.03	-1.16	.736	9.68	4.29	.00	.00
2B	22.80	.556	20.83	-7.135	1.69	-.41	.751	10.06	4.55	.00	.00
3B.	22.40	.549	20.05	-5.972	2.12	-1.14	.730	9.49	3.90	.00	.00
4B.	22.50	.550	19.90	-5.476	2.40	-1.57	.718	9.40	3.90	.00	.00
5B	22.50	.550	20.20	-6.214	2.01	-.70	.726	9.50	4.55	.00	.00
1C	22.70	.549	20.34	-6.301	1.97	-.22	.714	9.41	4.55	.00	.00
2C	22.60	.555	20.82	-7.878	1.49	.12	.754	10.00	5.59	.00	.00
3C	22.30	.552	20.08	-6.354	1.96	-.66	.730	9.51	4.16	.00	.00
4C	22.40	.556	20.08	-6.107	2.08	-.87	.726	9.57	4.42	.00	.00
5C	22.50	.552	19.93	-5.609	2.33	-1.23	.715	9.38	3.90	.00	.00
6C	22.40	.553	20.17	-6.338	1.97	-.72	.732	9.58	4.29	.00	.00
7C	22.30	.551	20.08	-6.260	2.00	-.93	.735	9.55	3.90	.00	.00
8C	23.10	.555	21.04	-7.003	1.73	-.27	.742	10.06	5.20	.00	.00
9C	22.70	.556	20.87	-7.561	1.57	-.27	.759	10.13	4.55	.00	.00
10C	22.50	.551	20.04	-5.814	2.21	-1.07	.720	9.44	3.90	.00	.00
1S	22.60	.558	20.50	-6.664	1.86	-.71	.744	9.92	4.94	.00	.00
2S	22.60	.555	20.55	-6.828	1.79	-.58	.746	9.89	4.55	.00	.00
3S	22.60	.553	20.11	-5.729	2.26	-1.27	.722	9.55	4.55	.00	.00
4S	22.60	.552	20.30	-6.115	2.06	-1.10	.735	9.70	4.42	.00	.00
5S	22.60	.551	20.30	-6.137	2.05	-1.00	.733	9.65	4.81	.00	.00
1T	22.70	.550	19.93	-5.323	2.50	-1.35	.703	9.28	4.42	.00	.00
2T	22.60	.553	20.40	-6.493	1.91	-.53	.732	9.67	3.51	.00	.00
3T	22.60	.551	20.01	-5.583	2.34	-1.28	.715	9.42	3.77	.00	.00
4T	22.60	.550	19.98	-5.565	2.34	-1.16	.710	9.34	3.77	.00	.00
5T	22.80	.552	20.66	-6.676	1.83	-.47	.737	9.81	4.55	.00	.00

AVERAGES: 70930 BASELINE W078 00 000

	22.60	.553	20.41	-6.481	1.93	-.75	.738	9.75	4.46	.00	.00
STD	.14	.002	.30	.465	.17	.31	.010	.23	.12	*	*

70930 W087CA001 (1E15) BI CRYSTAL

	22.59	.553	20.31	-6.317	2.01	-.78	.730	9.64	4.39	.00	.00
STD	.17	.002	.32	.645	.26	.41	.014	.24	.50	*	*

PERCENT OF BASELINE

	100.0	****	99.5	102.5	104	96.7	99.0	98.9	98.3	*****	*****
STD%	1.4	.9	3.1	17.7	24	117.7	3.3	5.0	14.2	*****	*****

70919 W088CR001(5E14) W058 00 000
 SOL6 1 /19/78 AM1: P0=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDE
1R*	22.50	.558	20.18	-6.311	2.00	-.27	.716	9.51	.00	.00	.00
1B.*	20.10	.561	16.98	-4.784	3.04	-.44	.635	7.57	.65	.00	.00
2P	20.90	.595	18.98	-6.821	1.93	-.61	.743	9.77	1.56	.00	.00
3B.*	20.90	.576	17.59	-4.563	3.34	-1.27	.641	8.15	.91	.00	.00
4B	20.50	.595	18.99	-8.208	1.52	-.19	.771	9.95	1.69	.00	.00
5B	21.00	.596	19.40	-7.903	1.60	-.36	.769	10.17	1.56	.00	.00
2C	21.50	.585	18.38	-4.641	3.29	-2.27	.675	8.98	1.04	.00	.00
3C	20.60	.552	17.55	-5.254	2.58	1.07	.625	7.51	.65	.00	.00
4C	20.60	.594	18.61	-6.460	2.08	-1.00	.740	9.57	1.56	.00	.00
5C	21.50	.596	19.51	-6.701	1.98	-.77	.744	10.08	1.69	.00	.00
6C	21.40	.599	19.69	-7.568	1.70	-.55	.766	10.38	1.95	.00	.00
7C	20.80	.587	17.92	-4.759	3.19	-2.57	.689	8.89	1.04	.00	.00
8C	20.50	.594	18.72	-7.080	1.84	-.74	.755	9.72	1.56	.00	.00
9C	20.80	.431	15.33	-3.659	3.63	1.31	.487	4.62	.52	.00	.00
1S	21.30	.592	19.21	-6.379	2.10	-.92	.736	9.81	1.56	.00	.00
2S	21.50	.574	18.07	-4.388	3.52	-2.11	.650	8.48	.65	.00	.00
3S	21.50	.574	18.12	-4.573	3.30	-1.24	.643	8.39	.65	.00	.00
4S	21.10	.586	19.00	-6.371	2.08	-.74	.730	9.54	1.17	.00	.00
5S	21.50	.597	20.02	-8.615	1.44	-.17	.781	10.60	1.95	.00	.00
1T	21.20	.569	17.69	-4.337	3.57	-1.85	.638	8.14	.91	.00	.00
2T	20.60	.587	18.23	-5.559	2.53	-1.69	.717	9.17	1.30	.00	.00
3T	20.80	.565	17.63	-4.788	3.04	-.65	.642	7.98	.65	.00	.00
4T	20.50	.580	17.74	-4.953	2.97	-1.99	.687	8.64	.91	.00	.00

AVERAGES: 70919 BASELINE W058 00 000

	20.80	.595	19.12	-7.644	1.69	-.38	.761	9.96	1.60	.00	.00
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STD	.22	.000	.19	.595	.18	.17	.013	.17	.06	*	*
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70919 W088CR001(5E14)

	21.04	.574	18.32	-5.652	2.64	-.99	.688	8.85	1.16	.00	.00
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STD	.39	.038	1.05	1.306	.70	1.04	.070	1.35	.46	*	*
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PERCENT OF BASELINE

	101.2	96.5	95.8	126.1	156	-58.3	90.5	88.9	72.5	*****	*****
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STD%	3.0	6.5	6.5	24.2	63	504.0	10.8	15.3	32.7	*****	*****
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ORIGINAL PAGE IS
OF POOR QUALITY

70922 *
 W089CU001 (1E15) W058 00 000
 SOL6 1 /12/78 AM1: PO=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(10)	N	R	FF	EFF	OCD	PCDA	PCDB
1R*	22.50	.559	20.18	-6.289	2.01	-.36	.718	9.55	.00	.00	.00
1B.*	20.30	.586	17.97	-5.585	2.51	-1.67	.717	9.02	2.34	.00	.00
2B.*	20.20	.582	17.41	-4.806	3.12	-2.49	.688	8.55	2.34	.00	.00
3B	20.90	.594	18.90	-6.710	1.97	-.31	.730	9.59	1.82	.00	.00
4B	20.30	.590	18.80	-8.131	1.53	-.34	.773	9.79	1.56	.00	.00
1C	21.30	.589	18.57	-5.036	2.92	-2.28	.703	9.33	1.30	.00	.00
2C.*	21.20	.585	17.69	-4.067	4.08	-3.98	.663	8.69	1.04	.00	.00
3C	21.40	.599	19.86	-8.319	1.50	-.18	.774	10.50	2.60	.00	.00
4C	21.30	.597	19.54	-7.368	1.75	-.56	.760	10.22	1.95	.00	.00
5C	21.20	.598	19.59	-7.949	1.59	-.34	.770	10.32	2.60	.00	.00
6C	21.20	.597	19.57	-7.825	1.62	-.40	.768	10.28	2.60	.00	.00
7C	21.40	.581	18.45	-4.917	2.99	-1.59	.677	8.91	1.04	.00	.00
8C	21.10	.586	18.61	-5.461	2.59	-1.63	.711	9.30	1.30	.00	.00
9C	21.30	.574	17.93	-4.518	3.37	-1.49	.644	8.33	.78	.00	.00
1S	21.40	.596	19.36	-6.491	2.06	-1.02	.743	10.02	1.95	.00	.00
2S	21.10	.595	19.45	-7.734	1.64	-.40	.765	10.16	1.56	.00	.00
3S	21.40	.596	19.10	-5.740	2.45	-1.92	.735	9.91	2.21	.00	.00
4S	21.40	.589	18.93	-5.552	2.53	-1.53	.715	9.52	1.56	.00	.00
5S	21.30	.590	18.68	-5.205	2.79	-2.09	.709	9.42	1.56	.00	.00
1T	21.30	.595	19.34	-6.745	1.96	-.77	.745	9.99	1.82	.00	.00
2T	21.50	.595	19.32	-6.162	2.21	-1.20	.735	9.94	1.56	.00	.00
3T	21.40	.604	19.85	-8.213	1.54	-.37	.777	10.62	2.60	.00	.00
4T	20.70	.597	19.05	-7.510	1.71	-.79	.770	10.06	2.34	.00	.00
5T	21.30	.601	19.90	-9.001	1.37	-.08	.786	10.64	2.60	.00	.00
6T	21.50	.599	20.03	-8.724	1.42	-.06	.780	10.62	2.60	.00	.00

AVERAGES: 70922 BASELINE W058 00 000

	20.60	.592	18.85	-7.421	1.75	-.32	.752	9.69	1.69	.00	.00
STD	.30	.002	.05	.711	.22	.01	.022	.10	.13	*	*

70922 W089CU001 (1E15)

	21.29	.594	19.22	-6.762	2.11	-.99	.740	9.90	1.92	.00	.00
STD	.18	.007	.56	1.382	.60	.70	.038	.61	.58	*	*

PERCENT OF BASELINE

	103.3	****	101.9	108.9	120	*****	98.5	102.2	113.8	*****	*****
STD%	2.4	1.5	3.2	29.1	54	230.7	8.0	7.4	45.8	*****	*****

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71028 W090MN001 LOW RESISTIVITY (7E14) W058 00 000
SOL6 1 /12/78 AM1: PO=91.60MW/CM*2 NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDE
1R*	22.50	.551	20.12	-6.149	2.04	-.43	.714	9.37	.00	.00	.00
1B*	20.80	.518	16.50	-4.075	3.61	.27	.560	6.38	.39	.00	.00
2B.*	20.90	.586	18.39	-5.402	2.63	-1.63	.707	9.16	1.04	.00	.00
3B*	21.00	.544	16.99	-4.169	3.65	-.41	.586	7.08	.52	.00	.00
4B.*	20.70	.578	17.74	-4.749	3.15	-2.03	.674	8.53	1.04	.00	.00
5B	20.40	.587	18.55	-6.955	1.86	-.41	.741	9.38	1.30	.00	.00
1C.*	19.60	.582	16.78	-4.563	3.40	-3.51	.690	8.33	1.04	.00	.00
2C	17.90	.580	16.18	-6.678	1.96	-.68	.735	8.06	1.04	.00	.00
3C	20.50	.547	16.58	-4.143	3.72	-.67	.589	6.98	.52	.00	.00
4C	19.00	.532	15.54	-4.361	3.37	-.33	.597	6.38	.65	.00	.00
5C*	19.10	.477	14.96	-4.038	3.43	.61	.544	5.24	.52	.00	.00
6C*	19.80	.487	15.69	-4.065	3.44	.16	.559	5.70	.52	.00	.00
7C	19.10	.567	16.23	-4.707	3.17	-1.72	.657	7.53	.91	.00	.00
8C*	19.80	.502	15.38	-3.902	3.81	.27	.540	5.68	.39	.00	.00
9C	20.10	.564	16.72	-4.296	3.62	-2.06	.635	7.61	.65	.00	.00
10C	20.10	.549	16.12	-4.039	3.91	-.84	.581	6.78	.65	.00	.00
11C	18.00	.582	16.69	-8.489	1.44	.17	.766	8.49	1.17	.00	.00
1S*	17.90	.486	14.07	-4.174	3.34	1.19	.542	4.99	.65	.00	.00
2S	18.90	.583	16.54	-5.302	2.72	-1.82	.699	8.15	.78	.00	.00
3S	20.30	.593	18.56	-7.193	1.80	-.57	.753	9.59	1.30	.00	.00
4S	20.00	.593	18.67	-8.939	1.37	-.06	.783	9.83	1.69	.00	.00
5S*	20.00	.504	15.92	-4.136	3.45	.34	.562	5.99	.52	.00	.00
1I.*	17.50	.570	14.67	-4.315	3.72	-3.68	.659	6.95	.91	.00	.00
2T*	19.80	.525	16.06	-4.364	3.30	.45	.579	6.37	.52	.00	.00
3T*	17.70	.527	14.14	-3.979	3.95	-1.59	.583	5.76	.52	.00	.00
4T.*	19.70	.476	13.63	-3.238	5.15	.66	.450	4.46	.39	.00	.00
5T	19.00	.556	15.59	-4.296	3.61	-1.10	.608	6.79	.39	.00	.00

AVERAGES: 71028 BASELINE W058 00 000

	20.40	.587	18.55	-6.955	1.86	-.41	.741	9.38	1.30	.00	.00
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STD	.00	.000	.00	.000	.00	.00	.000	.00	.00	*	*
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71028 W090MN001 LOW RESISTIVITY (7E14)

	19.35	.568	16.67	-5.677	2.79	-.88	.673	7.84	.89	.00	.00
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STD	.86	.019	.99	1.746	.93	.69	.073	1.08	.37	*	*
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PERCENT OF BASELINE

	94.9	96.7	89.9	118.4	150	-16.2	90.8	83.5	68.2	*****	*****
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STDZ	4.2	3.3	5.3	25.1	50	170.5	9.9	11.5	28.2	*****	*****
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ORIGINAL PAGE IS
OF POOR QUALITY

71031 W091CR-MN002 (5E14-5E14) W078 00 000
 SOL6 1 /19/78 AM1: P0=91.60MW/CM12 NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	FFF	OCD	PCDA	PCDB
1R*	22.50	.551	20.01	-5.905	2.16	-.63	.710	9.31	.00	.00	.00
1B.*	22.40	.547	20.01	-5.944	2.13	-1.02	.724	9.39	4.16	.00	.00
2B.	22.40	.548	20.04	-5.965	2.12	-1.14	.729	9.47	3.51	.00	.00
3B	22.20	.548	20.08	-6.595	1.85	-.55	.736	9.47	4.29	.00	.00
4B.*	22.10	.544	19.23	-5.029	2.69	-1.77	.696	8.85	2.60	.00	.00
1C	15.60	.474	13.48	-5.253	2.30	-.93	.669	5.24	.65	.00	.00
2C	17.50	.500	15.63	-6.352	1.82	-.02	.705	6.52	.91	.00	.00
3C	16.70	.489	14.74	-5.792	2.03	-.79	.699	6.04	.91	.00	.00
4C	17.10	.495	15.15	-5.940	1.98	-.54	.700	6.27	.65	.00	.00
5C	16.80	.492	14.38	-4.881	2.65	-1.74	.668	5.84	.65	.00	.00
6C	15.70	.476	13.39	-4.920	2.55	-1.35	.657	5.20	.65	.00	.00
7C	17.50	.501	15.72	-6.543	1.75	-.17	.717	6.65	.78	.00	.00
8C	17.80	.500	15.56	-5.420	2.28	-1.10	.690	6.49	.65	.00	.00
9C	16.70	.483	14.10	-4.645	2.81	-1.75	.650	5.54	.52	.00	.00
10C	15.40	.474	13.14	-4.872	2.59	-1.80	.663	5.12	.65	.00	.00
1S	17.80	.504	15.80	-5.888	2.03	-.91	.709	6.73	.65	.00	.00
2S	17.10	.498	15.14	-5.922	2.00	-.56	.700	6.30	.78	.00	.00
3S	17.20	.499	15.25	-5.900	2.02	-.83	.706	6.41	.91	.00	.00
4S	17.80	.502	15.63	-5.529	2.22	-1.12	.696	6.58	.78	.00	.00
5S	17.50	.498	15.27	-5.398	2.28	-1.02	.685	6.32	.65	.00	.00
1T	16.00	.484	13.79	-5.168	2.40	-1.00	.667	5.46	.65	.00	.00
2T	16.50	.484	14.41	-5.554	2.14	-.53	.679	5.74	.78	.00	.00
3T	16.10	.480	14.00	-5.420	2.21	-.74	.676	5.53	.78	.00	.00
4T	16.00	.480	13.88	-5.342	2.26	-.84	.674	5.47	.78	.00	.00
5T	15.90	.478	13.61	-4.962	2.52	-1.41	.663	5.33	.65	.00	.00
6T	15.90	.476	13.39	-4.593	2.84	-2.07	.650	5.20	.78	.00	.00

AVERAGES: 71031 BASELINE W078 00 000

	22.20	.548	20.08	-6.595	1.85	-.55	.736	9.47	4.29	.00	.00
STD	.00	.000	.00	.000	.00	.00	.000	.00	.00	*	*

71031 W091CR-MN002 (5E14-5E14)

	16.70	.489	14.55	-5.442	2.27	-1.01	.682	5.90	.72	.00	.00
STD	.78	.010	.38	.521	.30	.52	.020	.54	.10	*	*

PERCENT OF BASELINE

	75.2	89.2	72.4	117.5	123	16.1	92.7	62.3	16.9	*****	*****
STD%	3.5	1.9	4.4	7.9	16	94.8	2.7	5.8	2.4	*****	*****

71101 W092PH002 (2.8E16) W078 00 000
 SOL6 1 /19/78 AM1: P0=91.60MW/CM:2 NO AR COATING

ID	ISC	VOC	IP	LOG(I0)	N	R	FF	EFF	OCD	PCDA	PCDF
1R*	22.50	.555	20.11	-6.138	2.06	-.40	.713	9.41	.00	.00	.00
1B	22.40	.550	20.05	-6.113	2.06	-.69	.721	9.39	4.55	.00	.00
2B	22.10	.553	20.02	-6.608	1.87	-.74	.742	9.59	4.55	.00	.00
3B.	22.30	.550	19.85	-5.724	2.26	-1.37	.724	9.40	3.90	.00	.00
4B.*	21.80	.545	17.69	-3.556	4.79	-5.61	.650	8.16	3.12	.00	.00
5B.*	22.40	.547	19.13	-4.490	3.22	-2.71	.684	8.86	2.60	.00	.00
1C	22.30	.566	19.52	-5.144	2.71	-1.91	.706	9.43	3.51	.00	.00
2C	22.10	.561	19.05	-4.751	3.03	-2.29	.690	9.04	3.12	.00	.00
3C	22.30	.550	18.66	-4.275	3.50	-2.18	.648	8.40	1.30	.00	.00
4C	22.60	.564	19.78	-5.134	2.70	-1.90	.707	9.53	5.20	.00	.00
5C	22.10	.562	19.22	-4.960	2.84	-2.13	.700	9.19	2.73	.00	.00
6C	22.40	.565	19.60	-5.136	2.71	-1.86	.705	9.43	3.90	.00	.00
7C	22.60	.562	19.78	-5.104	2.71	-1.99	.708	9.51	4.55	.00	.00
8C	21.70	.564	19.30	-5.705	2.33	-1.48	.724	9.37	3.38	.00	.00
9C	22.40	.567	19.89	-5.672	2.35	-1.32	.719	9.66	4.55	.00	.00
10C	22.40	.566	19.51	-4.987	2.83	-2.10	.702	9.41	2.99	.00	.00
11C	22.00	.563	19.08	-4.894	2.91	-2.17	.696	9.12	2.99	.00	.00
12C	22.20	.565	19.64	-5.490	2.46	-1.60	.718	9.52	4.16	.00	.00
1S	22.20	.568	19.85	-5.918	2.23	-1.28	.730	9.73	4.55	.00	.00
2S	21.70	.565	18.85	-4.844	2.97	-2.71	.706	9.16	3.64	.00	.00
3S	22.30	.565	19.56	-5.234	2.63	-1.70	.706	9.40	3.25	.00	.00
4S	22.10	.565	19.45	-5.353	2.55	-1.62	.710	9.38	3.64	.00	.00
5S	22.50	.565	19.81	-5.319	2.57	-1.76	.714	9.59	3.90	.00	.00
1T	21.90	.563	19.43	-5.760	2.29	-.94	.711	9.27	4.16	.00	.00
2T	22.00	.567	19.68	-6.045	2.16	-.93	.724	9.55	3.51	.00	.00
3T	22.30	.562	20.13	-6.467	1.95	-.66	.734	9.73	4.68	.00	.00
4T	22.10	.561	19.93	-6.445	1.96	-.59	.731	9.58	4.55	.00	.00
5T	22.50	.559	19.80	-5.435	2.47	-1.19	.703	9.35	3.90	.00	.00

AVERAGES: 71101 BASELINE W078 00 000

	22.25	.552	20.04	-6.361	1.96	-.71	.732	9.49	4.55	.00	.00
STD	.15	.002	.01	.248	.10	.03	.011	.10	.00	*	*
	71101 W092PH002 (2.8E16)										
	22.21	.563	19.52	-5.367	2.58	-1.65	.709	9.38	3.73	.00	.00
STD	.25	.004	.36	.528	.36	.54	.017	.28	.83	*	*
PERCENT OF BASELINE											
	99.8	****	97.4	115.6	132	-32.0	96.9	98.8	82.1	*****	*****
STD%	1.8	.9	1.9	11.9	26	87.4	3.8	4.0	18.2	*****	*****